IN THE UNITED STATES DISTRICT COURT
FOR THE DISTRICT OF DELAWARE

In re:	)	
	)	MDL Docket No. 07-md-1848 (GMS)
REMBRANDT TECHNOLOGIES, LP PATENT LITIGATION	)	

JOINT APPENDIX OF INTRINSIC AND EXTRINSIC EVIDENCE FOR '627 PATENT

Collins J. Seitz, Jr. (#2237)
Francis DiGiovanni (#3189)
James D. Heisman (#2746)
Connolly Bove Lodge & Hutz LLP
1007 N. Orange Street
P.O. Box 2207
Wilmington, Delaware 19899
(302) 658-9141
cseitz@cblh.com
fdigiovanni@cblh.com
jheisman@cblh.com

Attorneys for Rembrandt Technologies, LP
and Rembrandt Technologies, LLC

Jack B. Blumenfeld (#1014)
Karen Jacobs Louden (#2881)
Morris, Nichols, Arsht & Tunnell LLP
1201 N. Market Street
P.O. Box 1347
Wilmington, DE 19899
(302) 658-9200
jblumenfeld@mnat.com
klouden@mnat.com

Liaison Counsel for '627 Patent
Infringement Defendants

Dated: July 7, 2008

JOINTLY SUBMITTED EXHIBITS

Tab	Description	Party Citing	Pages
1	U.S. Patent No. 5,243,627	Defendants Rembrandt	A001-A012

PLAINTIFFS' EXHIBITS

Tab	Description	Party Citing	Pages
2	U.S. Patent No. 4,677,625	Rembrandt	B001-B013
3	Chart of Rembrandt and All Other Parties' Proposed Constructions for U.S. Patent No. 5,243,627 and the Texas Court's Claim Constructions from Rembrandt Technologies, L.P. v. Comcast, Corp., et al.	Rembrandt	B014-B016
4	Newton's Telecom Dictionary , relevant pages	Rembrandt	B017-B018
5	Memorandum Opinion and Order in the Texas Court's Rembrandt Technologies, L.P. v. Comcast, Corp., et al. 05-443, Dated June 5, 2007	Rembrandt	B019-B040
6	Richard D. Gitlin Deposition dated June 23, 2008, relevant pages	Rembrandt	B041-B055

DEFENDANTS' EXHIBITS

Tab	Description	Party Citing	Pages
7	Declaration of Richard D. Gitlin	Defendants	D0001-D0018
	Exhibit A - Declaration of Richard D. Gitlin, Curriculum Vitae	Defendants	D0019-D0027

	Exhibit B - Declaration of Richard D. Gitlin, "Trellis-Coded Modulation with Redundant Signal Sets Part I: Introduction" *IEEE Communications Magazine*, Vol. 25, No. 2, pp. 5-11, February 1987	Defendants	D0028-D0034
	Exhibit C - Declaration of Richard D. Gitlin, "Trellis-Coded Modulation with Multidimensional Constellations", *IEEE Transactions on Information Theory*, Vol. 33, No. 4. July 1987	Defendants	D0035-D0053
	Exhibit D - Declaration of Richard D. Gitlin, U.S. Patent No. 4,641,327	Defendants	D0054-D0065
	Exhibit E - Declaration of Richard D. Gitlin, U.S. Patent No. 4,755,998	Defendants	D0066-D0078
	Exhibit F - Declaration of Richard D. Gitlin, U.S. Patent No. 5,214,656	Defendants	D0079-D0091
	Exhibit G - Declaration of Richard D. Gitlin, Robert G. Gallager, INFORMATION THEORY AND RELIABLE COMMUNICATION 287 (John Wiley & Sons 1968)	Defendants	D0092-D0097
	Exhibit H - Declaration of Richard D. Gitlin, U.S. Patent No. 4,677,625	Defendants	D0098-D0105
8	Claim Charts for U.S. Patent No. 5,243,627	Defendants	D106-D111
9	Richard D. Gitlin Deposition dated June 23, 2008	Defendants	D112-D184

TAB 1

US005243627A

United States Patent [19]

Betts et al.

[11] **Patent Number: 5,243,627**

[45] **Date of Patent: Sep. 7, 1993**

[54] **SIGNAL POINT INTERLEAVING TECHNIQUE**

[75] Inventors: **William L. Betts**, St. Petersburg; **Edward S. Zuranski**, Largo, both of Fla.

[73] Assignee: **AT&T Bell Laboratories**, Murray Hill, N.J.

[21] Appl. No.: **748,594**

[22] Filed: **Aug. 22, 1991**

[51] **Int. Cl.^{5}** **H04L 5/12**

[52] **U.S. Cl.** **375/39**; 375/60; 375/99; 371/43

[58] **Field of Search** 375/39, 58, 60, 99; 371/43, 37.5, 2.1, 45; 341/81

[56] **References Cited**

U.S. PATENT DOCUMENTS

3,988,677	10/1976	Fletcher et al.	371/45 X
4,677,624	6/1987	Betts et al.	375/39
4,945,549	7/1990	Simon et al.	375/53
5,029,185	7/1991	Wei	375/39 X

Primary Examiner—Curtis Kuntz
Assistant Examiner—Tesfaldet Bocure
Attorney, Agent, or Firm—Ronald D. Slusky; Gerard A. deBlasi

[57] **ABSTRACT**

Viterbi decoder performance in a data communication system using 2N-dimensional channel symbols N>1 can be further enhanced by an interleaving technique which uses a distributed trellis encoder in combination with a signal point interleaver.

24 Claims, 4 Drawing Sheets

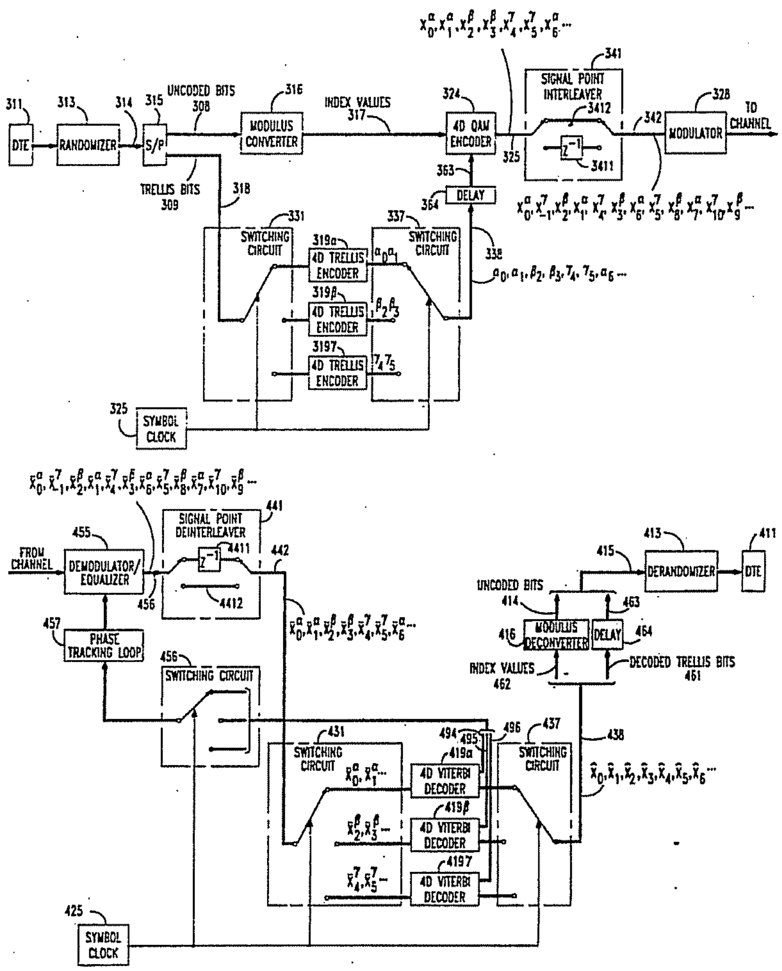


FIG. 1
PRIOR ART

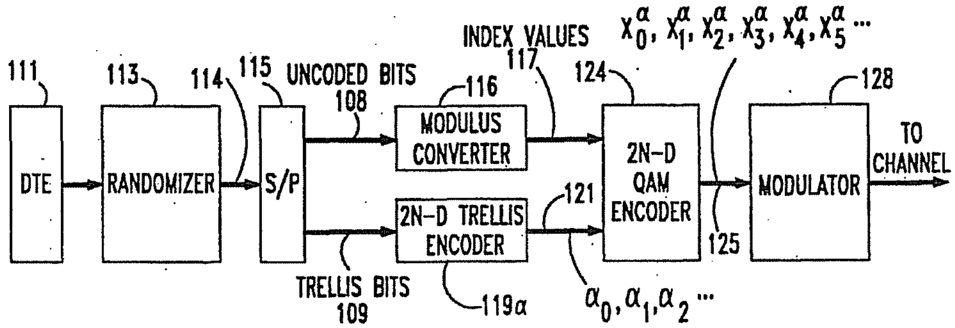
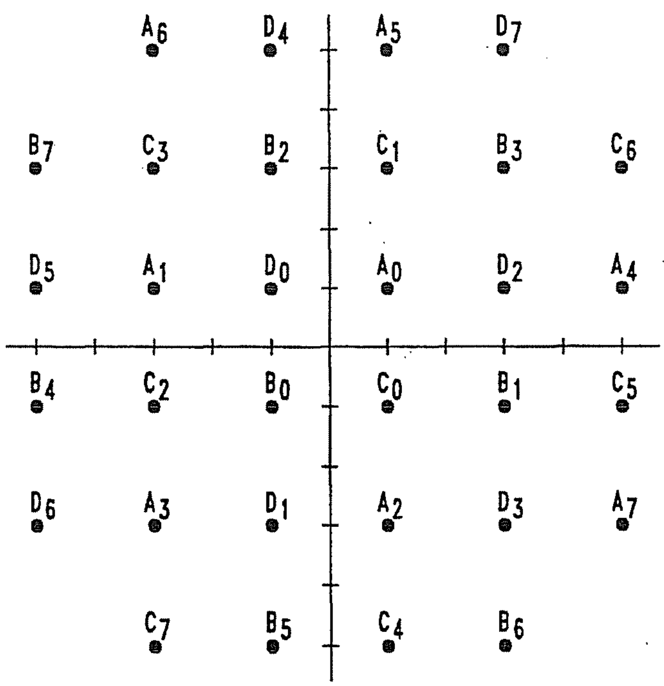


FIG. 2



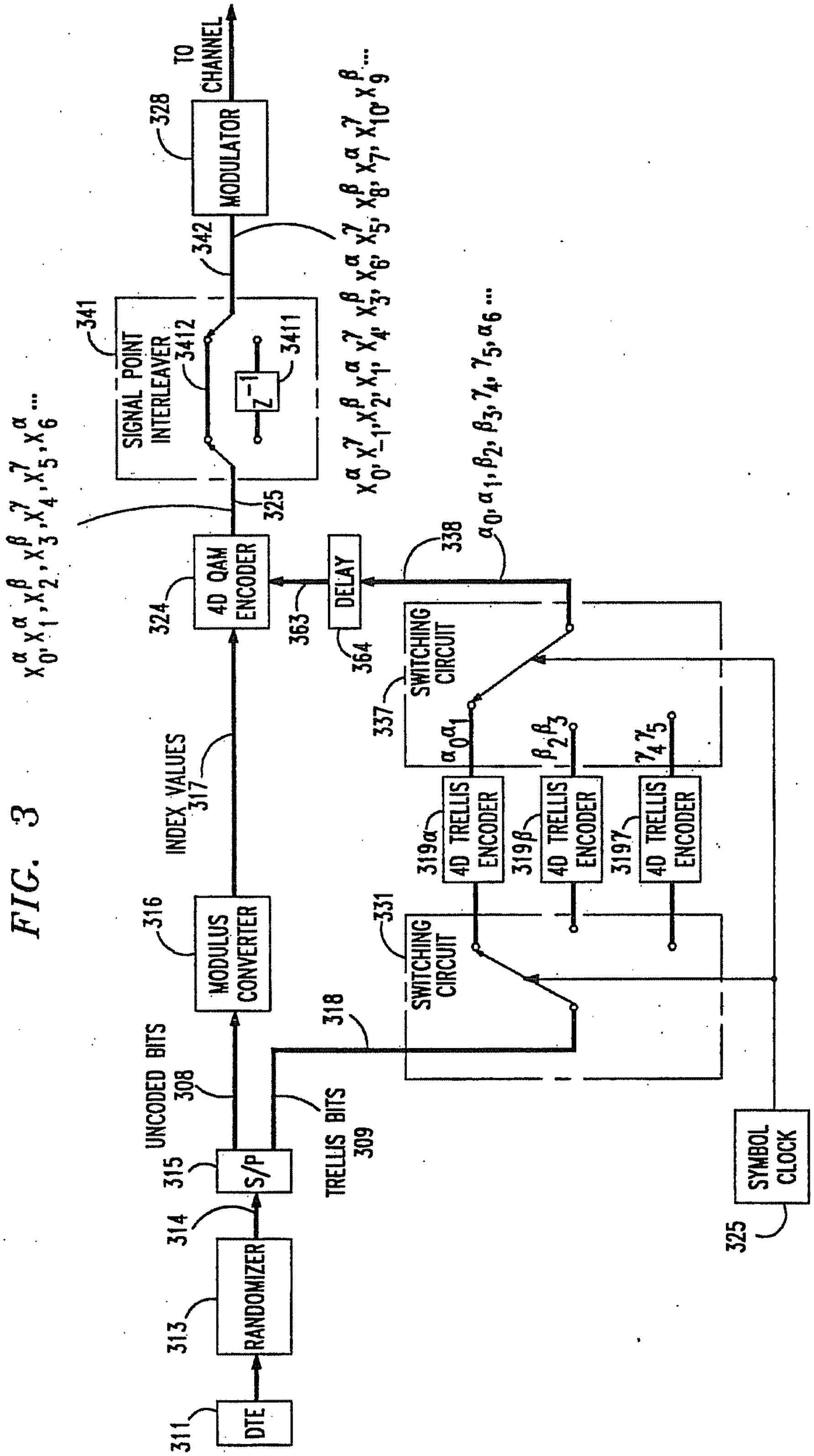
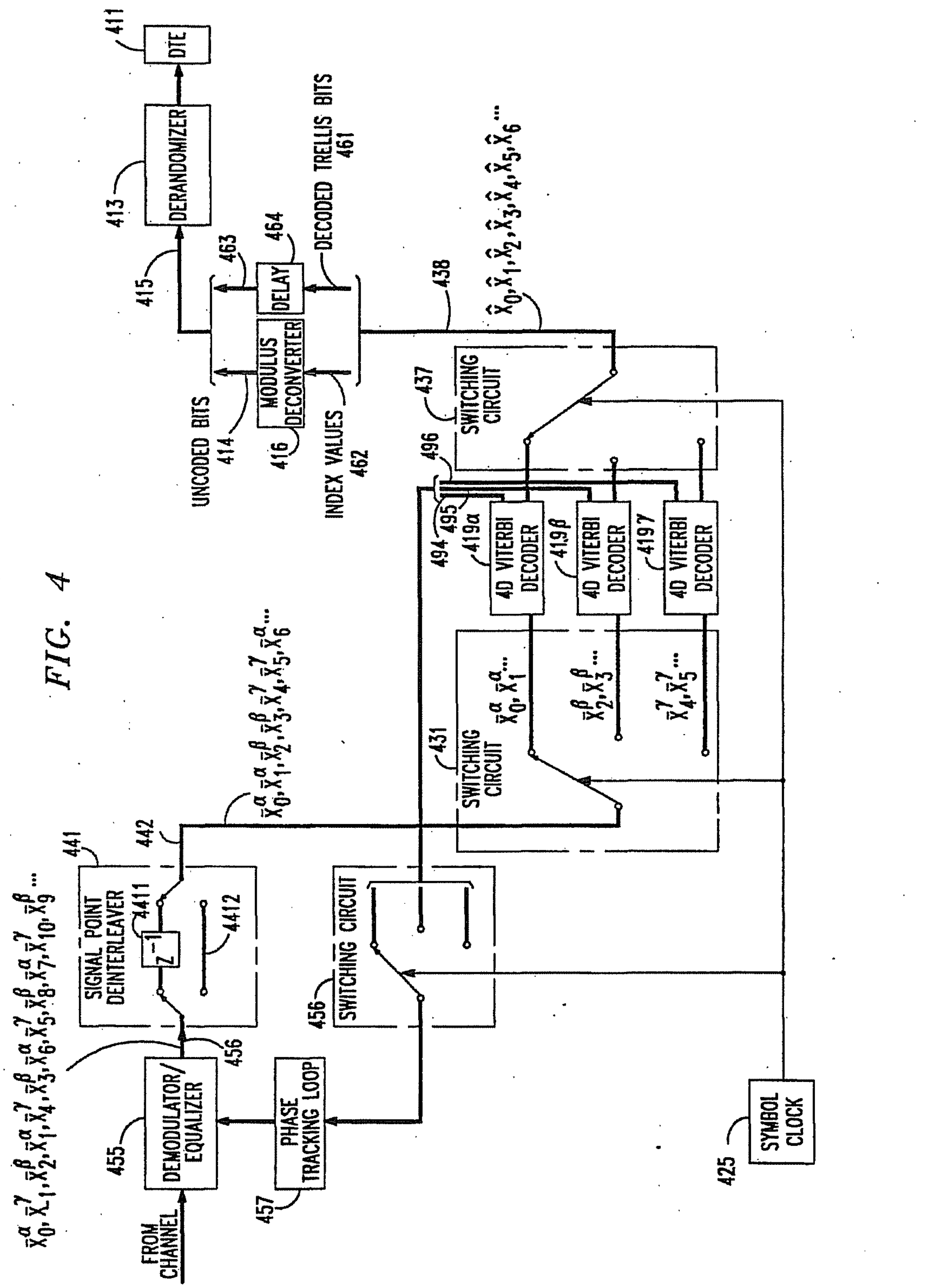

DTE
311
RANDOMIZER
313
314
S/P
315
UNCODED BITS
308
TRELLIS BITS
309
MODULUS CONVERTER
316
INDEX VALUES
317
318
SWITCHING CIRCUIT
331
4D TRELLIS ENCODER
319α
319β
319γ
SWITCHING CIRCUIT
337
DELAY
364
363
338
4D QAM ENCODER
324
325
SIGNAL POINT INTERLEAVER
341
3412
3411
342
MODULATOR
328
TO CHANNEL
SYMBOL CLOCK
325

FIG. 3



DTE
DERANDOMIZER
MODULUS DECONVERTER
DELAY
DECODED TRELLIS BITS 461
UNCODED BITS 414
INDEX VALUES 462
SWITCHING CIRCUIT
4D VITERBI DECODER
4D VITERBI DECODER
4D VITERBI DECODER
SWITCHING CIRCUIT
SIGNAL POINT DEINTERLEAVER
SWITCHING CIRCUIT
DEMODULATOR/ EQUALIZER
PHASE TRACKING LOOP
FROM CHANNEL
SYMBOL CLOCK

FIG. 4

FIG. 5

		4D SYMBOL		4D SYMBOL		4D SYMBOL		4D SYMBOL		4D SYMBOL		4D SYMBOL	
I	NOT INTERLEAVED ONE TRELLIS STAGE	x_0^α	x_1^α	x_2^α	x_3^α	x_4^α	x_5^α	x_6^α	x_7^α	x_8^α	x_9^α	x_{10}^α	...
II	NOT INTERLEAVED THREE TRELLIS STAGES	x_0^α	x_1^α	x_2^β	x_3^β	x_4^γ	x_5^γ	x_6^α	x_7^α	x_8^β	x_9^β	x_{10}^γ	...
III	INTERLEAVED ONE TRELLIS STAGE	x_0^α	x_{-1}^α	x_2^α	x_1^α	x_4^α	x_3^α	x_6^α	x_5^α	x_8^α	x_7^α	x_{10}^α	...
IV	INTERLEAVED TWO TRELLIS STAGES	x_0^α	x_{-1}^β	x_2^β	x_1^α	x_4^α	x_3^β	x_6^β	x_5^α	x_8^α	x_7^β	x_{10}^β	...
V	INTERLEAVED THREE TRELLIS STAGES	x_0^α	x_{-1}^γ	x_2^β	x_1^α	x_4^γ	x_3^β	x_6^α	x_5^γ	x_8^β	x_7^α	x_{10}^γ	...

FIG. 6

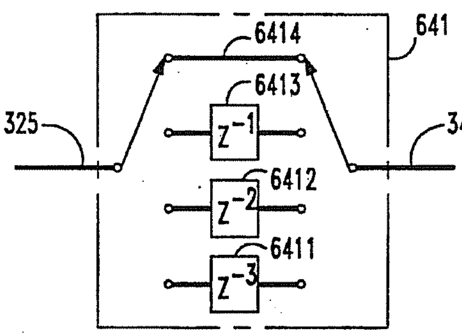
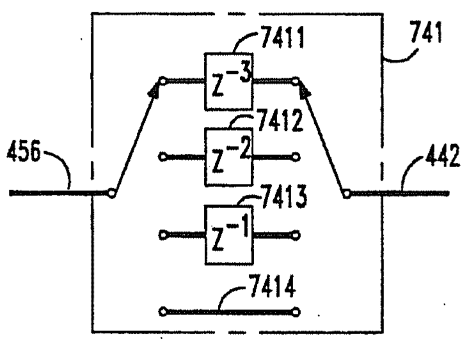


FIG. 7



SIGNAL POINT INTERLEAVING TECHNIQUE

BACKGROUND OF THE INVENTION

The present invention relates to the transmission of digital data over band-limited channels.

Over the years, the requirements of modern-day digital data transmission over band-limited channels—such as voiceband telephone channels—have resulted in a push for higher and higher bit rates. This push has led to the development and introduction of such innovations as adaptive equalization, multi-dimensional signal constellations, echo cancellation (for two-wire applications), and trellis coding. Today, the data rates achieved using these and other techniques are beginning to approach the theoretical limits of the channel.

It has been found that various channel impairments, whose effects on the achievable bit rate were relatively minor compared to, say, additive white Gaussian noise and linear distortion, have now become of greater concern. These include such impairments as nonlinear distortion and residual (i.e., uncompensated-for) phase jitter. Such impairments are particularly irksome in systems which use trellis coding. Indeed, it has been found that the theoretical improvement in Gaussian noise immunity promised by at least some trellis codes is not realized in real-world applications where these impairments are manifest. The principal reason this is so appears to be that the noise components introduced into the received signal samples are such as to worsen the effectiveness of the Viterbi decoder used in the receiver to recover the transmitted data.

U.S. Pat. No. 4,677,625, issued Jun. 30, 1987 to Betts et al, teaches a method and arrangement in which, through the use of a distributed trellis encoder/Viterbi decoder, the effects of many of these impairments can be reduced. The invention in the Betts et al patent recognizes that a part of the reason that the performance of the Viterbi decoder is degraded by these impairments is the fact that the noise components of channel symbols which closely follow one another in the transmission channel are highly correlated for many types of impairments. And it is that correlation which worsens the effect that these impairments have on the Viterbi decoder. Among the impairments whose noise is correlated in this way are impulse noise, phase "hits" and gain "hits." All of these typically extend over a number of adjacent channel symbols in the channel, and thus all result in channel symbol noise components which are highly correlated. The well-known noise enhancement characteristics of linear equalizers also induce correlated noise in adjacent channel symbols, as does uncompensated-for phase jitter. Also, the occurrence of one of the relatively high power points of the signal constellation can, in pulse code modulation (PCM) systems, for example, give rise to noise on adjacent channel symbols which, again, is correlated.

The Betts et al patent addresses this issue by distributing the outgoing data to a plurality of trellis encoders in round-robin fashion and interleaving the trellis encoder outputs on the transmission channel. In the receiver, the stream of received interleaved channel symbols is correspondingly distributed to a plurality of trellis decoders. Since the successive pairs of channel symbols applied to a particular trellis decoder are separated from one another as they traverse the channel, the correlation of the noise components of these channel symbol

pairs is reduced from what it would have otherwise been.

SUMMARY OF THE INVENTION

In accordance with the present invention, it has been realized that the Viterbi decoder performance in a data communication system using 2N-dimensional channel symbols can be further enhanced by an interleaving technique which uses, in combination, a) the aforementioned distributed trellis encoder/Viterbi decoder technique and b) a signal point interleaving technique which causes the constituent signal points of the channel symbols to be non-adjacent as they traverse the channel.

In preferred embodiments of the invention, the interleaving is carried out in such a way that every N^{th} signal point in the signal point stream traversing the channel is the N^{th} signal point of a respective one of the channel symbols. This criterion enhances the accuracy with which the phase tracking loop in the receiver performs its function.

Also in preferred embodiments, we have found that the use of three parallel trellis encoders in conjunction with a signal point interleaving regime in which the signal points of each channel symbol are separated from one another by three signaling intervals (bauds) provides an optimum or near-optimum tradeoff between signal point/channel symbol separation and the decoding delay that is caused by the interleaving.

BRIEF DESCRIPTION OF THE DRAWING

In the drawing,

FIG. **1** is a block diagram of the transmitter section of a prior art modem;

FIG. **2** is shows a signal constellation used by the transmitter of FIG. **1**;

FIG. **3** is a block diagram of the transmitter section of a modem employing four-dimensional channel symbols and embodying the principles of the invention;

FIG. **4** is a block diagram of the receiver section of a modem embodying the principles of the invention which processes the received four-dimensional channel symbols generated by the transmitter of FIG. **3**;

FIG. **5** is a signal point timing/sequencing chart helpful in explaining the principles of the present invention;

FIG. **6** is a signal point interleaver which can be used in the transmitter of FIG. **3** to interleave the signal points of eight-dimensional channel symbols; and

FIG. **7** is a signal point deinterleaver which can be used in the receiver of FIG. **4** to deinterleave the signal points of eight-dimensional channel symbols.

DETAILED DESCRIPTION

FIG. **1** depicts the transmitter section of a prior art modem employing a 2N-dimensional signaling scheme, $N \geqq 1$. The modem receives input information in the form of a serial bit stream from data terminal equipment (DTE) **111**—illustratively a host computer. That bit stream is then scrambled, or randomized, by randomizer **113** whose output bits are provided in serial form to serial-to-parallel (S/P) converter **115**.

Serial-to-parallel converter **115**, in turn, provides, during each of a succession of symbol intervals (comprised of N baud intervals), some predetermined number of parallel bits on lead **109** and some number of parallel bits on lead **108**. (It will be appreciated that whenever bits are provided in parallel in the modem, separate leads are required to carry each of the bits.) The bits on lead **109** are applied to trellis encoder **119**a,

and are referred to as the "trellis bits." The bits on lead **108** are applied to modulus converter **116**, and are referred to as the "uncoded bits."

To better understand how trellis encoder **119**α and modulus converter **116** work, reference is made to FIG. **2**, which shows the two-dimensional signal constellation that forms the basis of the 2N-dimensional signaling scheme illustratively used by the modem. This constellation is comprised of 32 signal points, which are divided into four subsets, A through D, each comprised of eight signal points. The eight points of subset A are explicitly labeled as A_0 through A_7. It may be noted that subsets C, B and D can be arrived at by clockwise rotation of subset A by 90, 180 and 270 degrees, respectively. (Conventional differential encoding circuitry within trellis encoder **119**α exploits this symmetry.) For reference, a single signal point of each of those subsets is also shown on FIG. **2**.

Consider, first, the case of N=1, i.e., a two-dimensional signaling scheme. In this case, one trellis bit on lead **109** would be expanded to two bits by trellis encoder **119**α on lead **121**. The four possible values of those three bits **00**, **01**, **10**, and **11** identify subsets A, B, C and D, respectively. The successive 2-bit words on lead **121** are represented as α_n, n=0,1,2. . . , where n is an index that advances at the baud rate. At the same time, three parallel bits would be provided on lead **108**. These are converted by modulus converter **116** into an index having a value within the range (decimal) 0 to 7. The index value, represented in binary form on lead **117**, selects a particular signal point from the subset identified on lead **121**. Thus if lead **121** carries the two bits **00** while lead **117** carries the three bits **001**, then signal point A_1 of the FIG. **2** constellation has been selected. The words on leads **117** and **121** are applied to QAM encoder **124** which generates, on lead **125**, values representing the I (in-phase) and Q (quadrature-phase) components of signal point A_1. The signal point generated on lead **125** in the n^{th} baud interval is denoted X_n^{α}, which is passed on to modulator **128** to generate a passband line signal which is applied to the communication channel. The superscript, α, indicates that the trellis encoder that was used to identify the subset for any particular signal point was trellis encoder **119**α. That is, of course, a trivial notation as far as FIG. **1** goes inasmuch as trellis encoder **119**α is the only trellis encoder in the modem. However, it is useful to introduce this notation because more than one trellis encoder stage is used in preferred embodiments of modems incorporating the principles of the present invention as shown in later FIGS.

In the case of N>1, the operation is similar. Now, however, the words on lead **109** are used by trellis encoder **119**α to sequentially identify on lead **121**N subsets, while the words on lead **108** are used to generate N corresponding index values on lead **117**. The N signal points identified in this way are the component signal points of a 2N-dimensional channel symbol, the first such symbol being comprised of the signal points X_0^{α}, . . . $X_{(N-1)}^{\alpha}$. For example, a modem in which the transmitter of FIG. **1** could be used may be a 14,400 bit per second modem using four-dimensional coding (i.e., N=2) and a baud rate of 3200. In this case, nine bits from S/P converter **115** are used for each four-dimensional symbol. Specifically, three parallel bits on lead **109** are expanded into four bits on lead **121** to identify a pair of subsets while six bits on lead **108** are used to select particular signal points from those two subsets. Those two signal points are thereupon communicated over the channel by QAM encoder **124** and modulator **128** as described above.

Note that, implementationally, the 2N-dimensional channel symbol is generated by having the trellis encoder identify, interdependently, N subsets of the two-dimensional constellation of FIG. **2**, then select a two-dimensional signal point from each of the subsets thus identified. The concatenation of the N two-dimensional signal points thus selected is the desired 2N-dimensional channel symbol. This process, however, can be understood as involving the direct selection of a 2N-dimensional channel symbol. Viewed in this context, the set of all possible combinations of N of the two-dimensional subsets identified by N successive trellis encoder outputs can be understood to be a set of 2N-dimensional subsets of a 2N-dimensional constellation, the latter being comprised of all possible combinations of N of the signal points of the two-dimensional constellation. A succession of N outputs from the trellis encoder identifies a particular one of the 2N-dimensional subsets and a succession of N outputs from the modulus converter selects a particular 2N-dimensional signal point from the identified 2N-dimensional subset.

Modulus converter **116** is illustratively of the type disclosed in co-pending, commonly-assigned U.S. patent application Ser. No. 588,658 filed Sep. 26, 1990 and allowed on May 21, 1991, hereby incorporated by reference. Modulus converter **116** provides the modem with the ability to support data transmission at various different bit rates. Assume, for example, that the rate at which bits are provided by DTE **111** decreases. The serial-to-parallel converter will continue to provide its outputs on leads **108** and **109** at the same baud rate as before. However, the upper limit of the range of index values that are provided by modulus converter **116** on lead **117** will be reduced, so that, effectively, each of the four subsets A through D, instead of having eight signal points, will have some smaller number. Conversely if the rate at which bits are provided by DTE **111** should increase over that originally assumed, the upper limit of the range of index values, and thus the number of parallel bits, that appear on lead **117** will be increased beyond eight and the constellation itself will be expanded to accommodate the larger number of signal points thus being selected. As an alternative to using a modulus converter, fractional bit rates can be supported using, for example, the technique disclosed in L. Wei, "Trellis-Coded Modulation with Multidimensional Constellations," *IEEE Trans. on Communication Theory*, Vol. IT-33, No. 4, July 1987, pp. 483-501.

Turning now to FIG. **3**, the transmitter portion of a modem embodying the principles of the invention is shown. This embodiment illustratively uses the aforementioned four-dimensional, i.e., N=2, signaling scheme. Many of the components are similar to those shown in FIG. **1**. Thus, in particular, the transmitter of FIG. **3**—which receives its input information in the form of a stream of input bits from DTE **311**—includes randomizer **313**, which supplies its output, on lead **314**, to S/P converter **315**. The latter outputs uncoded bits to modulus converter **316**. The transmitter further includes four-dimensional QAM encoder **324** and modulator **328**. The trellis bits, on lead **309**, are provided not to a standard single trellis encoder, but to a distributed trellis encoder comprised of three trellis encoder stages: trellis encoder stage **319**α, trellis encoder stage **319**β, and trellis encoder stage **319**γ.

Such a distributed trellis encoder, which is described in the aforementioned Betts et al patent, generates a plurality of streams of trellis encoded channel symbols in response to respective portions of the input information. Specifically, a three-bit word on lead **309** is supplied to trellis encoder stage **319**α. The next three-bit word on lead **309** is supplied to trellis encoder stage **319**β. The next three-bit word is supplied to trellis encoder stage **319**γ, and then back to trellis encoder stage **319**α. This distribution of the trellis bits to the various trellis encoder stages is performed by switching circuit **331** operating under the control of symbol clock **325**. The initial data word outputs of the trellis encoders are subset identifiers α_0 and α_1 for encoder stage **319**α, β_2 and β_3 for encoder stage **319**β, and γ_4 and γ_5 for encoder stage **319**γ, followed by α_6 and α_7 for encoder stage **319**α, and so forth. These are supplied to four-dimensional QAM encoder **324** by switching circuit **337**—also operating under the control of symbol clock **325**—on lead **338** through a one-symbol delay **364** and lead **363**, in order to compensate for a one-symbol delay caused by modulus converter **316**. Thus, the stream of subset identifiers on lead **338** is $\alpha_0, \alpha_1, \beta_2, \beta_3, \gamma_4, \gamma_5, \alpha_6$ . . . . Using the notation introduced above, then, the output of encoder **324** on lead **325** is the stream of signal points $X_0^\alpha, X_1^\alpha, X_2^\beta, X_3^\beta, X_4^\gamma, X_5^\gamma, X_6^\alpha$ . . . , which is comprised of three interleaved streams of trellis encoded channel symbols, these streams being $X_0^\alpha, X_1^\alpha, X_6^\alpha, X_7^\alpha, X_{12}^\alpha$ . . . ; $X_2^\beta, X_3^\beta, X_8^\beta, X_9^\beta, X_{14}^\beta$ . . . ; and $X_4^\gamma, X_5^\gamma, X_{10}^\gamma, X_{11}^\gamma, X_{16}^\gamma$ . . . . These, in turn, are supplied, in accordance with the invention, to signal point interleaver **341** which applies alternate ones of the signal points applied thereto to lead **3412**—which signal points appear immediately at the interleaver output on lead **342**—and to one-symbol (Z^{-1}) delay element **3411**, which appear on lead **342** after being delayed therein by one symbol interval. The resulting interleaved stream of trellis encoded signal points is $X_0^\alpha, X_{-1}^\gamma, X_2^\beta, X_1^\alpha, X_4^\gamma, X_3^\beta, X_6^\alpha, X_5^\gamma, X_8^\beta, X_7^\alpha, X_{10}^\gamma, X_9^\beta$ . . . (the signal point X_{-1}^γ being, of course, the signal point applied to interleaver **341** just ahead of signal point X_0^α).

A discussion and explanation of how the interleaving just described is advantageous is set forth hereinbelow. In order to fully set the stage for that explanation, however, it will be first useful to consider the receiver section of a modem which receives the interleaved signal point stream.

Thus referring to FIG. **4**, the line signal transmitted by the transmitter of FIG. **3** is received from the channel and applied to demodulator/equalizer **455** which, in conventional fashion—including an input from phase tracking loop **457**—generates a stream of outputs on lead **456** representing the demodulator/equalizer's best approximation of the values of the I and Q components of the signal points of the transmitted interleaved signal point stream. These outputs are referred to herein as the "received signal points." (Due to distortion and other channel impairments that the demodulator/equalizer is not able to compensate for, the I and Q components of the received signal points, instead of having exact integer values, can have any value. Thus a transmitted signal point having coordinates (3, −5) may be output by the demodulator/equalizer as the received signal point (2.945, −5.001).) The stream of received signal points on lead **456** is denoted $\overline{X}_0^\alpha, \overline{X}_{-1}^\gamma, \overline{X}_2^\beta, \overline{X}_1^\alpha, \overline{X}_4^\gamma, \overline{X}_3^\beta, \overline{X}_6^\alpha, \overline{X}_5^\gamma, \overline{X}_8^\beta, \overline{X}_7^\alpha, \overline{X}_{10}^\gamma, \overline{X}_9^\beta$ . . . .

The successive received signal points are deinterleaved in signal point deinterleaver **441**, which provides the opposite function to interleaver **341** in the transmitter. The output of deinterleaver **441** on lead **442** is thus $\overline{X}_0^\alpha, \overline{X}_1^\alpha, \overline{X}_2^\beta, \overline{X}_3^\beta, \overline{X}_4^\gamma, \overline{X}_5^\gamma, \overline{X}_6^\alpha$, . . . , etc. (Although not explicitly shown in the drawing, the same well-known techniques used in modems of this general kind to identify within the stream of received signal points the boundaries between successive symbols is used to synchronize the operation of signal point deinterleaver **441** to ensure that received signal points $\overline{X}_0^\alpha, \overline{X}_2^\beta, \overline{X}_4^\gamma$ . . . are applied to delay element **4411** while received signal points $\overline{X}_1^\alpha, \overline{X}_3^\beta, \overline{X}_5^\gamma$ . . . are applied to lead **4412**.)

The received signal points on lead **442** are then distributed by switching circuit **431** under the control of symbol clock **425** to a distributed Viterbi decoder comprised of 4D Viterbi decoder stages **419**α, **419**β and **419**γ. Specifically, received signal points $\overline{X}_0^\alpha$ and $\overline{X}_1^\alpha$ are applied to decoder stage **419**α; received signal points $\overline{X}_2^\beta$ and $\overline{X}_3^\beta$ are applied to decoder stage **419**β; and received signal points $\overline{X}_4^\gamma$ and $\overline{X}_5^\gamma$ are applied to decoder stage **419**γ. The outputs of the three decoder stages are then combined into a serial stream on lead **438** by switching circuit **437**, also operating under the control of symbol clock **425**. Those outputs, representing decisions as to the values of the transmitted signal points, are denoted $\hat{X}_0, \hat{X}_1, \hat{X}_2, \hat{X}_3, \hat{X}_4, \hat{X}_5, \hat{X}_6$, . . . , the α, β and γ superscripts no longer being needed.

In conventional fashion, the bits that represent each of the decisions on lead **438** can be divided into bits that represent a) the trellis bits that appeared on transmitter lead **309** and b) the index values that appeared on transmitter lead **317**. Those two groups of bits are provided in the receiver on leads **461** and **462**, respectively. The latter group of bits are deconverted by modulus deconverter **416** (also disclosed in the aforementioned '658 patent application) back to uncoded bit values on lead **414**. The operation of the modulus deconverter imparts a one-symbol delay to the bits on lead **414**. Accordingly, the bits on lead **461** are caused to be delayed by one symbol by delay element **464**. The resulting combined bits on lead **415** thus represent the stream of bits that appeared at the output of randomizer **313** in the transmitter. These are derandomized in the receiver by derandomizer **413** and the resulting derandomized bit stream is applied to DTE **411** which may be, for example, a computer terminal.

Referring to FIG. **5**, one can see the improvement that is achieved by the present invention.

Line I shows the stream of output signal points generated and launched into the channel using one stage of trellis encoding and no signal point interleaving. This is, of course, the prior art arrangement shown in FIG. **1**. Line II shows the effect of providing a three-stage distributed trellis encoder but still no signal point interleaving. This is the arrangement shown in the aforementioned Betts et al patent. Note that the signal points of each channel symbol operated on by a particular trellis encoder stage are adjacent in the output signal point stream. For example, the second signal point of the symbol $X_0^\alpha\ X_1^\alpha$—namely signal point X_1^α—is separated by five baud intervals from the first (closer) signal point of the symbol $X_6^\alpha\ X_7^\alpha$—namely signal point X_6^α. As noted earlier, such separation is advantageous because the channel symbols which are processed one after the other in a particular Viterbi decoder stage have noise components which are not highly correlated.

Note, however, that the individual signal points of each channel symbol, e.g., X_0^α and X_1^α, are adjacent to

one another as they pass through the channel; and since all the signal points of a channel symbol must be processed serially in the same Viterbi decoder stage, this means that the Viterbi decoder must process adjacent signal points that have highly correlated noise components.

It is to this end that signal point interleaver **341** is included within the transmitter in accordance with the invention. Firstly, it may be noted from Line III that using the signal point interleaver without the distributed trellis encoder—an arrangement not depicted in the drawing—will, advantageously, cause the signal points from the same channel symbol to be non-adjacent. Moreover, there is further advantage in that a pair of channel symbols processed serially by Viterbi decoder stage **419**α traverses the channel separated by five baud intervals rather than three, thereby providing greater decorrelation of the noise components thereof. Compare, for example, the span of baud intervals occupied by signal points X_0^α and X_1^α, X_2^α and X_3^α in Line I and the span of baud intervals occupied by the same signal points in Line III. Disadvantageously, however, the use of a single trellis encoding stage brings back the problem that the distributed trellis encoder solves, as described above. Thus, for example, although signal points X_0^α and X_1^α, which are from the same channel symbol, are separated from one another when traversing the channel, we find that, disadvantageously, signal points X_2^α and X_1^α, which are signal points from two different channel symbols which will be processed serially by the Viterbi decoder, traverse the channel adjacent to one another.

Line IV shows that using the signal point interleaver with a two-stage trellis encoder—also an arrangement not depicted in the drawing—provides some improvement. Firstly, it may be noted that, as in Line III, signal points from the same channel symbol remain separated by three baud intervals. Additionally, pairs of channel symbols processed sequentially by a given Viterbi decoder stage—such as the channel symbols comprised of signal points X_0^α and X_1^α, X_4^α and X_5^α—are still non-adjacent and, indeed, are now separated by seven baud intervals, which is even greater than the separation of five baud intervals provided in Line III. Moreover, certain signal points that traverse the channel adjacent to one another and which are from channel symbols which would have been decoded sequentially in the one-trellis-encoding-stage case are, in the two-trellis-encoding-stage case of Line IV, processed by different Viterbi decoding stages. Signal points X_2^β and X_1^α are such a pair of signal points. Note, however, that, disadvantageously, signal points X_1^α and X_4^α traverse the channel serially, and are from channel symbols which are serially processed by the "α" Viterbi decoder stage.

Referring, however, to Line V, which depicts the stream of signal points output by the transmitter of FIG. **3**, it will be seen that, in accordance with the invention, there is still a non-adjacency—indeed, a separation of at least three baud intervals—between a) the signal points which belong to any particular channel symbol (and which, therefore, are processed serially by a particular Viterbi decoder stage) and b) the signal points which belong to channel symbols which are processed serially by a Viterbi decoder stage. Thus, for example, signal points X_1^α and X_4^γ are now processed by different Viterbi decoder stages. Moreover, pairs of channel symbols processed sequentially by a given Viterbi decoder stage—such as the channel symbols comprised of signal points X_0^α and X_1^α, X_6^α and X_7^α—are now separated by none baud intervals.

Using more than three trellis encoder stages in the distributed trellis encoder and/or a signal point interleaver that separates signal points from the same channel symbol by more than three baud intervals would provide even greater separation and could, therefore, potentially provide even greater improvement in Viterbi decoding. However, such improvement comes at a price—that price being increased decoding delay—particularly as the number of trellis encoders is increased beyond three. An engineering trade-off can be made, as suits any particular application.

Moreover, it is desirable for the signal point interleaver to provide a sequence in which every N^{th} signal point in the interleaved signal point stream is the N^{th} signal point of a channel symbol. (The reason this is desirable is described in detail hereinbelow.) In the case of an $N=2$, four-dimensional signaling scheme, this means that every second, that is "every other," signal point in the interleaved stream is the second signal point of the channel symbol from which it comes. In the case of an $N=4$, eight-dimensional signaling scheme, this means that every fourth signal point in the interleaved stream is the fourth signal point of the channel symbol from which it comes. Indeed, this criterion is in fact satisfied in the embodiment of FIG. **3**. Note that each one of signal points X_0^α, X_2^β, X_4^γ, X_6^α, . . . , which appear as every other signal point in the interleaved stream, is the second signal point of one of the four-dimensional channel symbols. Note that not all rearrangements of the signal points will, in fact, satisfy this criterion, such as, if the two signal points of a channel symbol are separated by two, rather than three, baud intervals.

Satisfying the above criterion is advantageous because it enhances the accuracy with which phase tracking loop **457** performs its function. This is so because the arrival of an N^{th} signal point of a given symbol means that all the signal points comprising that channel symbol have arrived. This, in turn, makes it possible to form a decision as to the identity of that channel symbol by using the minimum accumulated path metric in the Viterbi decoder stages. (Those decisions are fed back to the tracking loop by decoder stages **419**α, **419**β **419**γ on leads **494**, **495** and **496**, respectively, via switching circuit **456**.) Without having received all of the signal points of a channel symbol, one cannot take advantage of the accumulated path metric information but, rather, must rely on the so-called raw sliced values, which is less accurate. By having every N^{th} signal point in the interleaved stream be the N^{th} signal point of a channel symbol, we are guaranteed that the time between adjacent such path metric "decisions" supplied to the phase tracking loop is, advantageously, never more than N baud intervals.

The foregoing merely illustrates the principles of the invention. Thus although the illustrative embodiment utilizes a four-dimensional signaling scheme, the invention can be used with signaling schemes of any dimensionality. In the general, 2N-dimensional, case each stage of the distributed trellis encoder would provide N two-dimensional subset identifiers to switching circuit **337** before the latter moves on to the next stage. And, of course, each stage of the distributed Viterbi decoder would receive N successive received signal points. The distributed trellis encoder and distributed Viterbi decoder can, however, continue to include three trellis

encoders and still maintain, independent of the value of N, a separation of three baud intervals in the channel between signal points that are from channel symbols that are adjacent in the trellis encoder. If a greater separation of such signal points is desired, more stages can be added to the distributed trellis encoder/Viterbi decoder, just as was noted above for the four-dimensional case. However, when dealing with 2N-dimensional signaling where $N>2$, it is necessary to add additional delay elements to the signal point interleaver/deinterleaver in order to maintain a three-baud-interval separation among the signal points from any given channel symbol.

Consider, for example, the case of $N=4$, i.e., an eight-dimensional case. Looking again at FIG. **3**, the three (8D) stages of the distributed trellis encoder would generate the three streams of subset identifiers $\alpha_0\ \alpha_1\ \alpha_2\ \alpha_3\ \alpha_{12} \ldots$, $\beta_4\ \beta_5\ \beta_6\ \beta_7\ \beta_{16} \ldots$, and $\gamma_8\ \gamma_9\ \gamma_{10}\ \gamma_{11}\ \gamma_{20} \ldots$, respectively. This would lead to the following stream of signal points of eight-dimensional trellis encoded channel symbols at the output of the QAM encoder on lead **325**: $X_0^\alpha\ X_1^\alpha\ X_2^\alpha\ X_3^\alpha\ X_4^\beta\ X_5^\beta\ X_6^\beta\ X_7^\beta\ X_8^\gamma\ X_9^\gamma X_{10}^\gamma\ X_{11}^\gamma\ X_{12}^\alpha \ldots$ Signal point interleaving could be carried out by substituting signal point interleaver **641** of FIG. **6** for interleaver **341**. Interleaver **641**, in addition to direct connection **6414**, includes one-, two-, and three-symbol delay elements **6413, 6412** and **6411**, respectively.

The signal points on lead **325**, after passing through interleaver **641**, would appear on lead **342** in the following order: $X_0^\alpha\ X_{-3}^\gamma\ X_{-6}^\beta\ X_{-9}^\alpha\ X_4^\beta\ X_1^\alpha\ X_{-2}^\gamma\ X_{-5}^\beta\ X_8^\gamma\ X_5^\beta\ X_2^\alpha\ X_{-1}^\gamma\ X_{12}^\alpha\ X_9^\gamma\ X_6^\beta\ X_3^\alpha\ X_{16}^\beta\ X_{13}^\alpha\ X_{10}^\gamma\ X_7^\beta \ldots$ where signal points with negative subscripts are, of course, signal points that arrived before signal point X_0^α and were already stored in the delay elements **6411, 6412** and **6413**. Examination of this signal point stream will reveal that there is either a three- or five-baud separation between signal points of channel symbols that are processed sequentially by the same trellis encoder stage, e.g., X_3^α and X_{12}^α; that adjacent signal points of any one channel symbol, e.g., X_0^α and X_1^α, are separated by five baud intervals; and that the four signal points comprising any particular one channel symbol are separated by fifteen baud intervals.

FIG. **7** shows the structure of a deinterleaver **741** that could be used in the receiver of FIG. **4** in place of deinterleaver **441** in order to restore the signal points of the eight-dimensional channel symbols to their original order. This structure, which is the inverse of interleaver **641**, includes delay stages **7411, 7412** and **7413**, as well as direct connection **7414**.

It will be appreciated that, although various components of the modem transmitter and receiver are disclosed herein for pedagogic clarity as discrete functional elements and indeed—in the case of the various switching circuits—as mechanical elements, those skilled in the art will recognize that the function of any one or more of those elements could be implemented with any appropriate available technology, including one or more appropriately programmed processors, digital signal processing (DSP) chips, etc. For example, multiple trellis encoders and decoders can be realized using a single program routine which, through the mechanism of indirect addressing of multiple arrays within memory, serves to provide the function of each of the multiple devices.

It will thus be appreciated that those skilled in the art will be able to devise numerous arrangements which, although not explicitly shown or described herein, embody the principles of the invention and are within its spirit and scope.

We claim:

1. Apparatus for forming a stream of trellis encoded signal points in response to input information, said apparatus comprising

means for generating a plurality of streams of trellis encoded channel symbols in response to respective portions of said input information, each of said channel symbols being comprised of a plurality of signal points, and

means for interleaving the signal points of said generated channel symbols to form said stream of trellis encoded signal points, said interleaving being carried out in such a way that the signal points of each channel symbol are non-adjacent in said stream of trellis encoded signal points and such that the signal points of adjacent symbols in any one of said channel symbol streams are non-adjacent in said stream of trellis encoded signal points.

2. The apparatus of claim **1** wherein said means for generating generates three of said streams of trellis encoded channel symbols, and wherein said means for interleaving causes there to be interleaved between each of the signal points of each channel symbol at least two signal points from other channel symbols of said streams of trellis encoded channel symbols.

3. The apparatus of claim **1** wherein said channel symbols are 2N-dimensional channel symbols, $N>1$, and wherein said means for interleaving causes every N^{th} signal point in said interleaved signal point stream to be the N^{th} signal point of a respective one of said channel symbols.

4. The apparatus of claim **2** wherein said channel symbols are 2N-dimensional channel symbols, $N>1$, and wherein said means for interleaving causes every N^{th} signal point in said interleaved signal point stream to be the N^{th} signal point of a respective one of said channel symbols.

5. A modem comprising

means for receiving a stream of input bits,

means for dividing said stream of input bits into a stream of uncoded bits and a plurality of streams of trellis bits,

means for independently trellis encoding each of said plurality of streams of trellis bits to generate respective streams of data words each identifying one of a plurality of predetermined subsets of the channel symbols of a predetermined 2N-dimensional constellation, N being an integer greater than unity, each of said channel symbols being comprised of a plurality of signal points,

means for selecting an individual channel symbol from each identified subset in response to said stream of uncoded bits to form a stream of channel symbols, and

means for generating a stream of output signal points, said signal point stream being comprised of the signal points of the selected channel symbols, the signal points of said signal point stream being sequenced in such a way that signal points that are either a) part of the same channel symbol, or b) part of channel symbols that are adjacent to one another in said channel symbol stream, are separated in said output stream by at least one other signal point.

6. The apparatus of claim **5** wherein said trellis encoding means includes a plurality of trellis encoder stage

means for trellis encoding respective ones of said streams of trellis bits.

7. The apparatus of claim 5 wherein said means for selecting includes means for modulus converting said stream of uncoded bits.

8. The apparatus of claim 5 wherein said channel symbols are 2N-dimensional channel symbols, $N>1$, and wherein said means for generating causes every N^{th} signal point in said stream of output signal points to be the N^{th} signal point of a respective one of said channel symbols.

9. Receiver apparatus for recovering information from a received stream of trellis encoded signal points, said signal points having been transmitted to said receiver apparatus by transmitter apparatus which generates said signal points by generating a plurality of streams of trellis encoded channel symbols in response to respective portions of said information, each of said channel symbols being comprised of a plurality of signal points, and by interleaving the signal points of said generated channel symbols to form said stream of trellis encoded signal points, said interleaving being carried out in such a way that the signal points of each channel symbol are non-adjacent in said stream of trellis encoded signal points and such that the signal points of adjacent symbols in any one of said channel symbol streams are non-adjacent in said stream of trellis encoded signal points,

said receiver apparatus comprising

means for deinterleaving the interleaved signal points to recover said plurality of streams of trellis encoded channel symbols, and

a distributed Viterbi decoder for recovering said information from the deinterleaved signal points.

10. The apparatus of claim 9 further comprising

a phase tracking loop, and

means for adapting the operation of said phase tracking loop in response to minimum accumulated path metrics in said distributed Viterbi decoder.

11. A method for forming a stream of trellis encoded signal points in response to input information, said method comprising the steps of

generating a plurality of streams of trellis encoded channel symbols in response to respective portions of said input information, each of said channel symbols being comprised of a plurality of signal points, and

interleaving the signal points of said generated channel symbols to form said stream of trellis encoded signal points, said interleaving being carried out in such a way that the signal points of each channel symbol are non-adjacent in said stream of trellis encoded signal points and such that the signal points of adjacent symbols in any one of said channel symbol streams are non-adjacent in said stream of trellis encoded signal points.

12. The method of claim 11 wherein said generating step generates three of said streams of trellis encoded channel symbols, and wherein said interleaving step causes there to be interleaved between each of the signal points of each channel symbol at least two signal points from other channel symbols of said streams of trellis encoded channel symbols.

13. The method of claim 11 wherein said channel symbols are 2N-dimensional channel symbols, $N>1$, and wherein said interleaving step causes every N^{th} signal point in said interleaved signal point stream to be the N^{th} signal point of a respective one of said channel symbols.

14. The method of claim 12 wherein said channel symbols are 2N-dimensional channel symbols, $N>1$, and wherein said interleaving step causes every N^{th} signal point in said interleaved signal point stream to be the N^{th} signal point of a respective one of said channel symbols.

15. A method for use in a modem, said method comprising the steps of

receiving a stream of input bits,

dividing said stream of input bits into a stream of uncoded bits and a plurality of streams of trellis bits,

independently trellis encoding each of said plurality of streams of trellis bits to generate respective streams of data words each identifying one of a plurality of predetermined subsets of the channel symbols of a predetermined 2N-dimensional constellation, N being an integer greater than unity, each of said channel symbols being comprised of a plurality of signal points,

selecting an individual channel symbol from each identified subset in response to said stream of uncoded bits to form a stream of channel symbols, and

generating a stream of output signal points, said signal point stream being comprised of the signal points of the selected channel symbols, the signal points of said signal point stream being sequenced in such a way that signal points that are either a) part of the same channel symbol, or b) part of channel symbols that are adjacent to one another in said channel symbol stream, are separated in said output stream by at least one other signal point.

16. The method of claim 15 wherein in said trellis encoding step a plurality of trellis encoder stages trellis encode respective ones of said streams of trellis bits.

17. The method of claim 15 wherein said selecting step includes the step of modulus converting said stream of uncoded bits.

18. The method of claim 15 wherein said channel symbols are 2N-dimensional channel symbols, $N>1$, and wherein said generating step causes every N^{th} signal point in said stream of output signal points to be the N^{th} signal point of a respective one of said channel symbols.

19. A method for use in a receiver to recover information from a received stream of trellis encoded signal points, said signal points having been transmitted to said receiver apparatus by a method which includes the steps of

generating a plurality of streams of trellis encoded channel symbols in response to respective portions of said information, each of said channel symbols being comprised of a plurality of signal points, and

interleaving the signal points of said generated channel symbols to form said stream of trellis encoded signal points, said interleaving being carried out in such a way that the signal points of each channel symbol are non-adjacent in said stream of trellis encoded signal points and such that the signal points of adjacent symbols in any one of said channel symbol streams are non-adjacent in said stream of trellis encoded signal points,

said method comprising the steps of

deinterleaving the interleaved signal points to recover said plurality of streams of trellis encoded channel symbols, and

using a distributed Viterbi decoder to recover said information from the deinterleaved signal points.

20. The method of claim 19 wherein said receiver includes a phase tracking loop and wherein said method comprises the further step of adapting the operation of said phase tracking loop in response to minimum accumulated path metrics in said distributed Viterbi decoder.

21. Data communication apparatus comprising

means for receiving input information,

means for generating a plurality of streams of trellis encoded channel symbols in response to respective portions of said input information, each of said channel symbols being comprised of a plurality of signal points,

means for interleaving the signal points of said generated channel symbols to form a stream of trellis encoded signal points, said interleaving being carried out in such a way that the signal points of each channel symbol are non-adjacent in said stream of trellis encoded signal points and such that the signal points of adjacent symbols in any one of said channel symbol streams are non-adjacent in said stream of trellis encoded signal points,

means for applying the stream of trellis encoded signal points to a transmission channel,

means for receiving the stream of trellis encoded signal points from the channel,

means for deinterleaving the interleaved signal points to recover said plurality of streams of trellis encoded channel symbols, and

a distributed Viterbi decoder for recovering said information from the deinterleaved signal points.

22. The apparatus of claim 21 wherein said means for generating generates three of said streams of trellis encoded channel symbols, and wherein said means for interleaving causes there to be interleaved between each of the signal points of each channel symbol at least two signal points from other channel symbols of said streams of trellis encoded channel symbols.

23. The apparatus of claim 21 wherein said channel symbols are 2N-dimensional channel symbols, $N>1$, and wherein said means for interleaving causes every N^{th} signal point in said interleaved signal point stream to be the N^{th} signal point of a respective one of said channel symbols.

24. The apparatus of claim 22 wherein said channel symbols are 2N-dimensional channel symbols, $N>1$, and wherein said means for interleaving causes every N^{th} signal point in said interleaved signal point stream to be the N^{th} signal point of a respective one of said channel symbols.

* * * * *

TAB 2

United States Patent [19]
Betts et al.

[11] **Patent Number: 4,677,625**
[45] **Date of Patent: Jun. 30, 1987**

[54] **DISTRIBUTED TRELLIS ENCODER**

[75] Inventors: **William L. Betts**, St. Petersburg; **Kenneth Martinez**, Pinellas Park; **Gordon Bremer**, Clearwater, all of Fla.

[73] Assignee: **Paradyne Corporation**, Largo, Fla.

[21] Appl. No.: **707,084**

[22] Filed: **Mar. 1, 1985**

[51] **Int. Cl.**[4] **G06F 11/10**; H03M 13/22

[52] **U.S. Cl.** .... **371/43**; 340/347 DD; 371/2; 375/26; 375/39

[58] **Field of Search** .... 340/347 DD; 371/43–45, 371/2; 360/39–42; 375/25, 34, 39

[56] **References Cited**

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4,500,994	2/1985	McCallister et al.	371/43
4,536,878	8/1985	Rattlingourd et al.	371/43

Primary Examiner—T. J. Sloyan
Attorney, Agent, or Firm—Kane, Dalsimer, Sullivan, Kurucz

[57] **ABSTRACT**

In the transmitter of a data communication system using QAM, a plurality of trellis coders with delay units are used for forward error correction. The output of each encoder is modulated using QAM to generate sequential baud signal elements. The redundant data bits generated are distributed between several non-consecutive bauds. Likewise, at the receiver a plurality of distributed convolutional decoders are utilized to decode the received signal element. The distributed trellis decoder is self-synchronizing.

11 Claims, 4 Drawing Figures

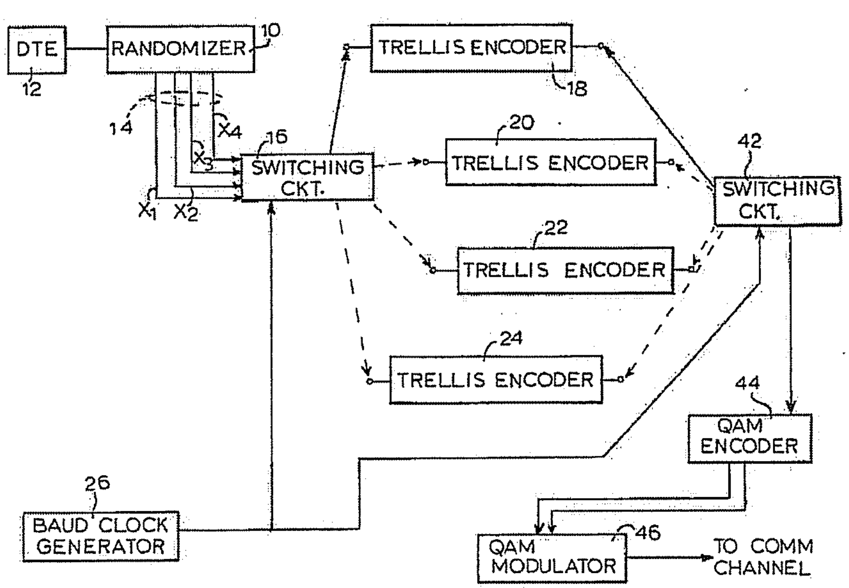
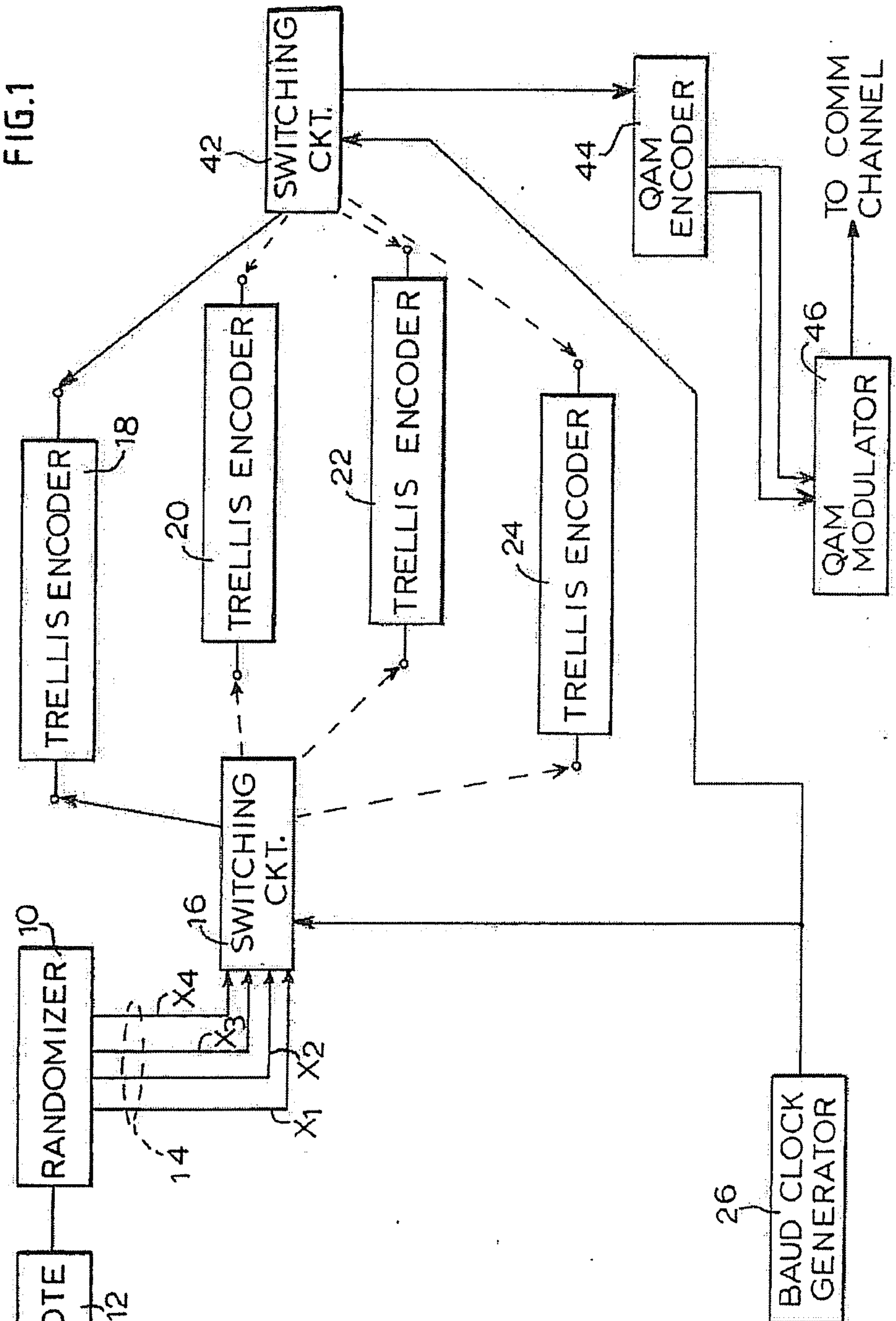


FIG.1



DTE
12
RANDOMIZER
10
14
X1
X2
X3
X4
SWITCHING CKT.
16
TRELLIS ENCODER
18
TRELLIS ENCODER
20
TRELLIS ENCODER
22
TRELLIS ENCODER
24
SWITCHING CKT.
42
QAM ENCODER
44
QAM MODULATOR
46
TO COMM CHANNEL
BAUD CLOCK GENERATOR
26

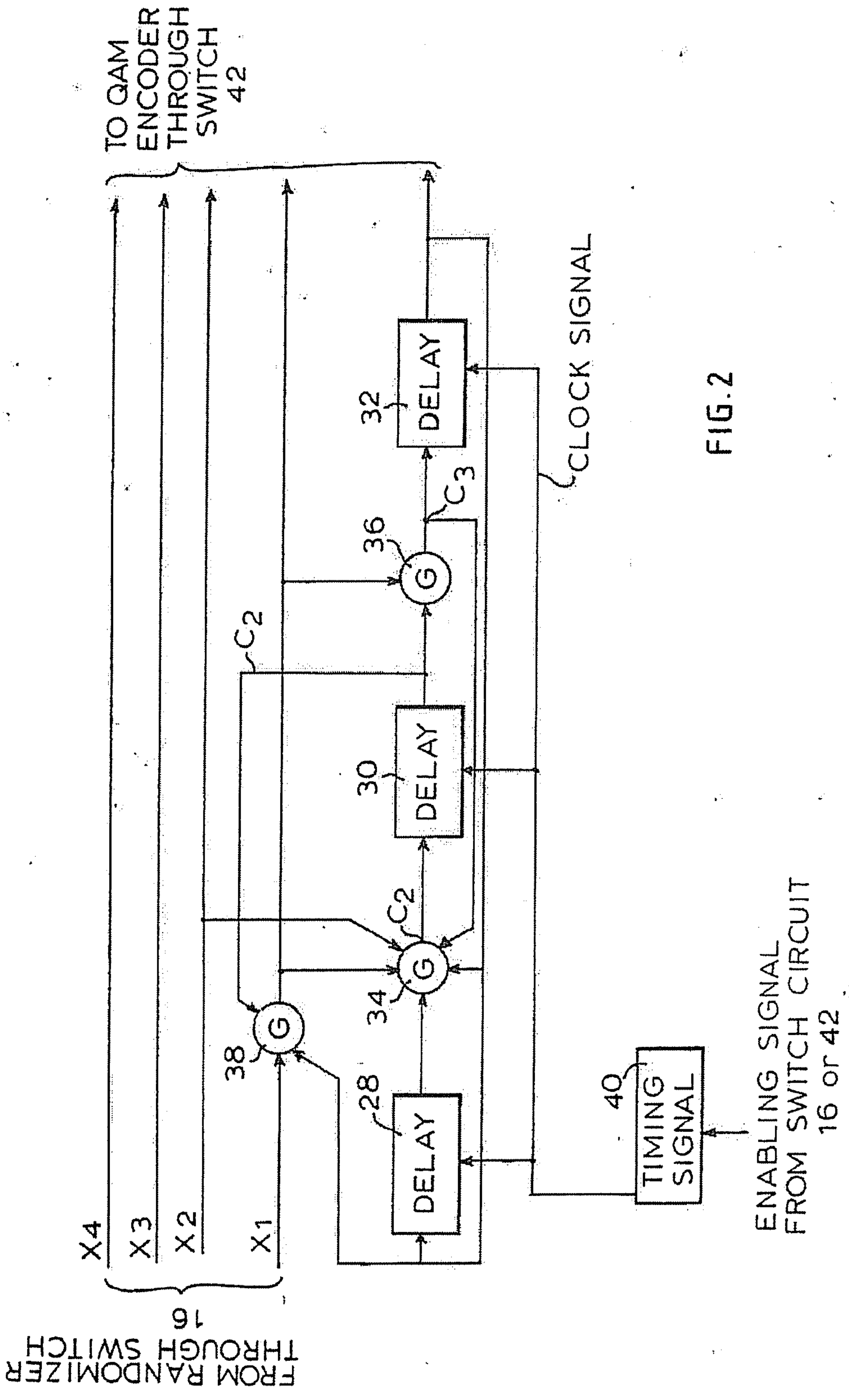
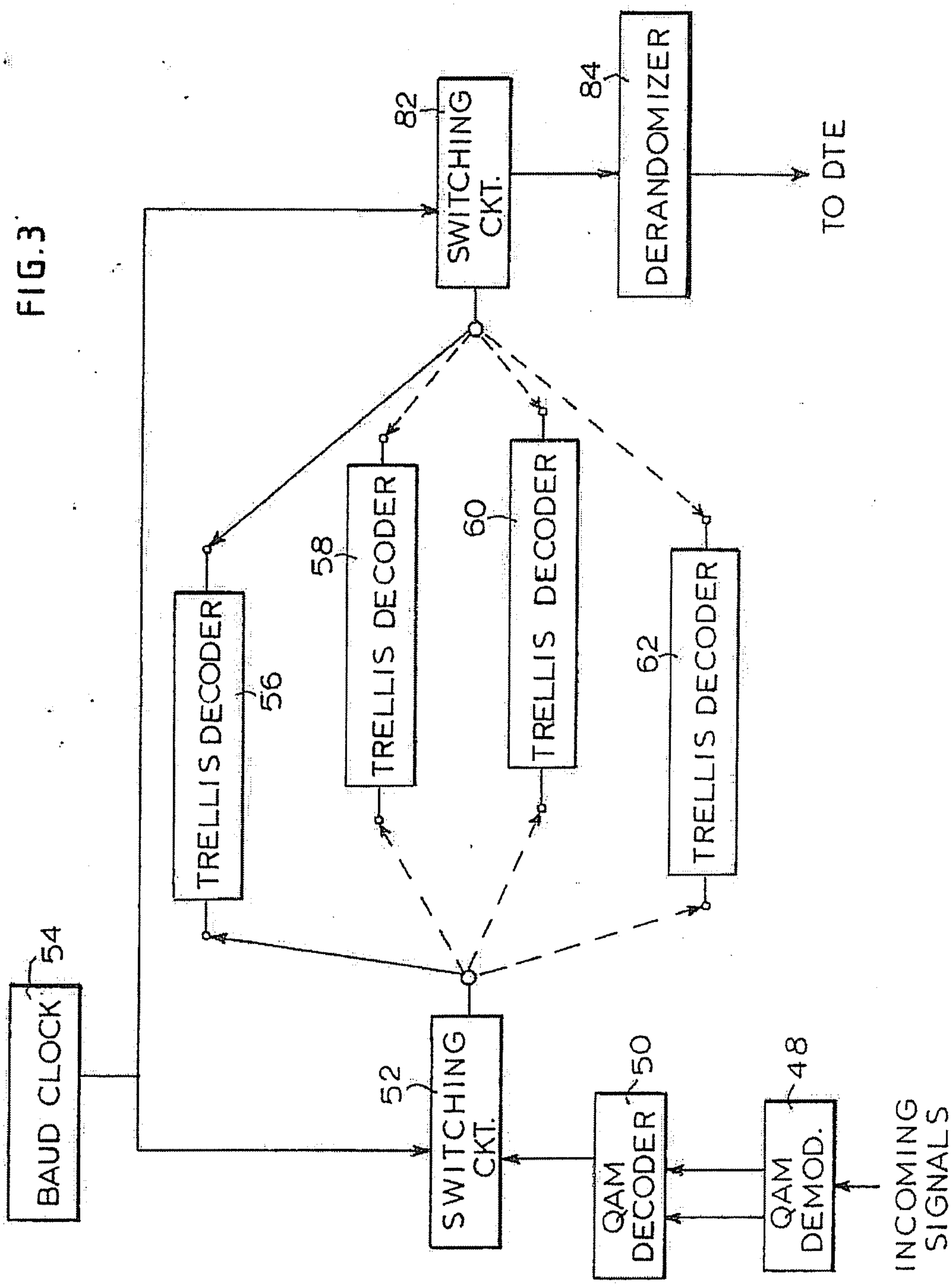

TO QAM ENCODER THROUGH SWITCH 42
X4
X3
X2
X1
DELAY
DELAY
DELAY
28
30
32
G
G
G
34
36
38
C_2
C_2
C_3
CLOCK SIGNAL
TIMING SIGNAL
40
ENABLING SIGNAL FROM SWITCH CIRCUIT 16 or 42
FROM RANDOMIZER THROUGH SWITCH 16

FIG. 2



BAUD CLOCK
54
SWITCHING CKT.
52
QAM DECODER
50
QAM DEMOD.
48
INCOMING SIGNALS
TRELLIS DECODER
56
TRELLIS DECODER
58
TRELLIS DECODER
60
TRELLIS DECODER
62
SWITCHING CKT.
82
DERANDOMIZER
84
TO DTE

FIG. 3

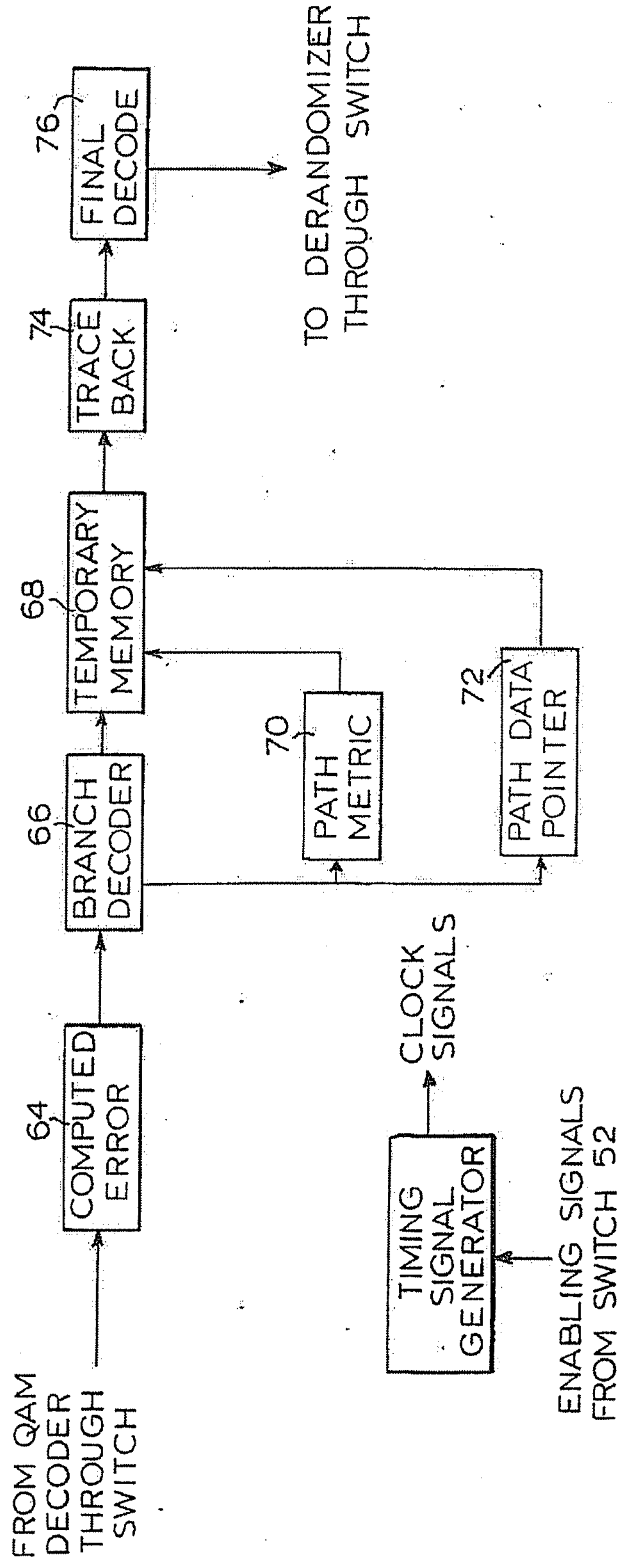

FROM QAM DECODER THROUGH SWITCH
64
COMPUTED ERROR
66
BRANCH DECODER
68
TEMPORARY MEMORY
74
TRACE BACK
76
FINAL DECODE
TO DERANDOMIZER THROUGH SWITCH
70
PATH METRIC
72
PATH DATA POINTER
CLOCK SIGNALS
TIMING SIGNAL GENERATOR
ENABLING SIGNALS FROM SWITCH 52

FIG. 4

DISTRIBUTED TRELLIS ENCODER

RELATED APPLICATIONS

The subject matter of this application is related to U.S. applications Ser. No. 707,085 entitled Self-Synchronizing Interleaver for Trellis Encoder used in Wireline Modems and Ser. No. 707,083 entitled Self-Synchronizing De-Interleaver for Viterbi Decoder Used in Wireline Modems, filed on even date herewith and incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of Invention

This invention pertains to an apparatus and method of encoding binary bits and more particularly to a method and apparatus for making use of a forward error correction scheme for a reduced number of errors at a given signal-to-noise ratio.

2. Description of the Prior Art

Communication networks using high speed data rates require high signal-to-noise ratios for proper data transmission. Numerous schemes and combinations thereof have been proposed to reduce the number of errors at these given signal-to-noise ratios. For example, in U.S. Pat. No. 4,077,021 to Csajka et al a forward error correcting scheme is described making use of the so-called Viterbi algorithm. In a further development described by the CCITT study group XVII, Contribution No. D180, in October, 1983, entitled TRELLIS-CODED MODULATION SCHEME WITH 8-STATE SYSTEMATIC ENCODER AND 90 SYMMETRY FOR USE IN DATA MODEMS TRANSMITTING 3-7 BITS PER MODULATION INTERVAL a two-dimensional trellis for a quadrature amplitude modulation scheme is disclosed having 90° symmetry which results in a 4db gain in the signal-to-noise ratio. Typically, in forward error coding, redundant bits are added systematically to the data bits so that normally only predetermined transitions from one sequential group of bits (corresponding to bauds) to another are allowed. There is an inherent correlation between these redundant bits over consecutive bauds. At the receiver each baud is tentatively decoded and then analyzed based on past history, and the decoded bits are corrected if necessary. However, it was found that certain types of relatively long error signals, such as for exmaple, low frequenty phase jitter, cause a constant phase error in the signal constellation for extended (consecutive baud) periods of time. This type of error prevents or inhibits the correction of the received bits using the schemes described above.

OBJECTIVES AND SUMMARY OF THE INVENTION

A principal objective of the present invention is to provide a device and method for data communication in which the effects of long bursts of error signals such as low frequency phase jitter are minimized.

A further objective is to provide a method of adapting a standard modem to perform the subject method and to provide a method that is self-synchronizing.

Other objectives and advantages of the invention shall become apparent from the following description of the invention.

In the present invention the correlation of the redundant bits of different baud signals is distributed in time prior to encoding at the transmitter. A distributed trellis

encoding scheme is used to obtain the redundant bits. At the receiver the received bauds are decoded using a plurality of distributed decoders which extract samples from multiple bauds for trellis decoding. The result is similar to that achieved by interleaving but avoids synchronization problems associated with the conventional complex interleaving processes.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 shows the elements of a data transmitter constructed in accordance with the invention;

FIG. 2 shows the elements of a distributed trellis encoder;

FIG. 3 shows the elements of a receiver for receiving data from the transmitter of FIG. 1; and

FIG. 4 shows the elements of a distributed trellis decoder.

DETAILED DESCRIPTION OF THE INVENTION

As shown in FIG. 1, a transmitter according to this invention comprises a randomizer 10 which receives serially a stream of data bits from DTE 12. The randomizer scrambles the bits in a preselected pattern and generates randomized bits on parallel output lines 14 identified as X1, X2, X3 and X4.

These output lines are fed by an electronic switching circuit 16 to a plurality of identical trellis encoders 18, 20, 22 and 24.

The electronic switching circuit 16 switches the signals from the randomizer 10 to one of the trellis encoders 18, 20, 22 and 24, in accordance with a baud clock signal generated by baud clock generator 26. In other words, for each baud period all the randomizer outputs X1, X2, X3 and X4 are fed to one of the encoders. Details of the trellis encoders 18, 20, 22 and 24 are shown in FIG. 2.

Each encoder comprises three delay units 28, 30 and 32 which are adapted to generate a delay of one baud period. The encoder further comprises three gates 34, 36 and 38. These gates may be for example XOR (exclusive -OR) gates.

The trellis encoder shown in FIG. 2 is well known in the art and need not be described any further. Preferably all the elements of the encoder are digital elements which are enabled by appropriate clocking signals from timing signal generator 40. The timing signal generator is enabled only when it receives an appropriate signal from switching circuit 16. Thus each encoder is active only when it is addressed by switching circuit 16. At all other times, the trellis encoders are idle.

Outputs Y0, Y1, X2, X3 and X4 are fed from the respective trellis encoders by a second electronic switching circuit 42 to QAM (quadrature amplitude modulation) encoder 44. Switching circuit 42 is also enabled by baud clock generator 26 so that it operates simultaneously with switching circuit 16. QAM encoder 44 selects a point of a preselected signal constellation corresponding to the inputs from circuit 42 and generates an in-phase and a quadrature output signal corresponding to said point. These output signals are fed to a QAM modulator 46 which generates corresponding analog QAM signals having a baud period equal to the period of the signals generated by signal generator 26. The signals from modulator 46 are transmitted over a common data communication channel to a receiver.

In effect the bits of several consecutive signals are spaced out over several bauds by the distributed trellis encoders.

At the receiver, illustrated in FIG. 3, the incoming analog signals are demodulated by a QAM demodulator **48** which generates an in-phase and a quadrature signal which are fed to a QAM decoder **50**. The QAM decoder **50** selects a point on the signal constellation closest to the actual point corresponding to the signals received from QAM demodulator **48**. The bits corresponding to said point are sent to a third electronic switching circuit **52** having a period equal to the baud period of the received signals. Circuit **52** accesses sequentially one of four distributed trellis decoders **56, 58, 60** and **62** in response to the switching signal from generator **54**. Thus all the binary signals from QAM decoder **50** corresponding to each received QAM signal are sent to one of the trellis decoders. The four trellis decoders are standard decoders well known in the art. One such decoder is shown in FIG. 4.

In a typical trellis decoder, the signals from the QAM decoder (in the present case, via switching circuit 52) are fed into an error computer circuit **64** which generates an error signal based on previously received signals. This error signal is fed to a branch decoder **66**. The branch decoder uses the trellis branch rules (predetermined in accordance with the Viterbi algorithm) to generate a set of possible points corresponding to the received point. These set of points are stored in temporary memory **68**. The decoder then searches through the points of the set to calculate the point with the smallest errors in accordance with appropriate constants stored in the path metric memory **70** and path pointer memory **72**. The smallest error is used by trace back memory **74** to track back the last 4–16 bauds (in accordance with a preselected well-known scheme) to generate the final received point. The final received point of the set of points in memory **68** is fed to final decoder **76** as the received point.

As with the encoder of FIG. 2, each decoder comprises digital elements which are enabled by a timing signal generator **78**.

The timing signal generator is enabled by an appropriate signal from switching circuit **52** only when the respective decoder is addressed by the switching circuit. Generator **78** generates clocking signals for the various decoder elements. Thus each decoder **56, 68, 60** and **62** is active only when it is addressed by switching circuit **52**, and otherwise it is idle.

The output of each decoder is accessed sequentially by a fourth electronic switching circuit **82** which is synchronized by the baud clock generator **54** so that it is in step with switching circuit **52**. In other words, each trellis decoder is accessed simultaneously by switch circuits **52** and **82**. The switching circuit **82** feeds the signals from the decoders to derandomizer **84** for reversing the effects of randomizer **10** and then to a user DTE.

It can be seen from the above description that switching circuits **16** and **52** acts as multiplexers while switch circuits **42** and **82** act as demultiplexers. The effect of this switching is to interleave the data bits at the transmitter across four bauds, and deinterleave these bits at the receiver. Obviously the trellis encoders are self-synchronized so that no synchronizing signals are needed between the transmitter and receiver

In the above description consecutive bits are interleaved across four bauds by using four distributed trellis encoders and decoders. Obviously if more encoders and decoders are used the number of bauds over which interleaving occurs increases.

It should be appreciated that the invention makes use of standard QAM encoders, modulators, decoders, demodulators and standard trellis encoders and decoders which are well known in the art. Furthermore, while baud clock generators **26** and **54** are described as separate elements, in practice they can be incorporated in the QAM modulator and demodulator respectively. All the circuits of FIGS. 1 and 3 may be implemented by using a digital microprocessor.

Obviously, numerous modifications to the subject application may be made without departing from the scope of the invention as defined in the appended claims.

What is claimed is:

1. A data transmission section for a modem coupled to a channel for sending data signals comprising:

1. A plurality of trellis encoders, each trellis encoder having an input for receiving n plain text bits, each encoder being provided to interleave bits received by the encoder during a first baud period with bits received during more than two previous baud periods to generate n trellis encoded bits, k, being larger than one; in a single baud period, each trellis encoder having means for delaying at least some of said n plain text bits so that they may be outputted and combined with bits outputted from one or more other trellis encoders during single baud periods;
2. encoder activating means for selectively activating only one of said trellis encoders for one baud period in a preselected sequence whereby bits received during a baud period i are interleaved with bits received during a baud period i-k;
3. signal encoding means for converting encoded bits into signals suitable for transmission over said channel; and
4. transmitter switching means for feeding n plain text bits per baud period to the activated trellis encoder and for sending the encoded bits from the activated trellis encoder to the signal encoding means.

2. A receiver section for a modem receiving data signals from a channel, said signals having been trellis encoded by interleaving bits corresponding to a baud period i with bits corresponding to a baud period i-k, k being larger than two, and having:

1. a demodulator and a decoder connected to the output of said demodulator for converting analog data signals from said channel into multiple series of bits, each series of bits substantially corresponding to a point of said analog data signal's preselected signal constellation;
2. k trellis decoders, each trellis decoder having an input from said decoder for receiving series of bits from said decoder and generating n bits of plain text bits corresponding to n bits received at least during two previous baud periods;
3. decoder activating means for activating only one of said trellis decoders during one baud period in another predetermined sequence; and
4. receiver switching means for feeding n encoded bits to the activated decoder and for collecting n plain text bits from the activated decoder.

3. A method of transmitting a plurality of input data bits over a channel by quadrature amplitude modulator comprising:

providing a plurality of trellis encoders, each encoder using an identical scheme to interleave bits received during a first baud period with bits received during more than two earlier baud periods preceding said first baud period to generate output bits;

activating each of said trellis encoders in a preselected order for a baud period;

feeding bits which occur during a single baud period to only one of said plurality of trellis encoders;

delaying at least some of said bits in said one trellis encoder during a single baud period;

combining bits which have been outputted from said one trellis encoder with bits which have been outputted from one or more different trellis encoders for transmission during a single baud period; and

quadrature amplitude modulating output bits of each activated trellis encoder.

4. A system for transmitting data signals over a data channel comprising:

a. a data transmission section coupled to said channel for sending data signals and having:

1. A plurality of trellis encoders, each trellis encoder having an input for receiving n plain text bits each encoder being provided to combine bits received by the encoder during more than two previous baud periods with bits received during a previous baud period to generate n trellis encoded bits in a single baud period, each trellis encoder having means for delaying at least some of said n plain text bits so that they can be outputted and combined with bits outputted from one or more other trellis encoders during single baud periods;
2. encoder activating means for selectively activating only one of said trellis encoders for one baud period in a preselected sequence;
3. signal encoding means for converting encoded bits into signals suitable for transmission over said channel; and
4. transmitter switching means for feeding n plain text bits per baud period to the activated trellis encoder and for sending the encoded bits from the activated trellis encoder to the signal encoding means; and

b. a receiver section for receiving data signals from said channel, and having:

1. a demodulator and a decoder connected to the output of said demodulator for converting analog data signals from said channel into multiple series of bits, each series of bits substantially corresponding to a point of said analog data signal's preselected signal constellation of;
2. a plurality of trellis decoders equal in number to the trellis encoders, each decoder generating n bits of plain text bits corresponding to n bits received by the encoder during a baud period and n bits received at least during a previous baud period;
3. decoder activating means for activating only one of said trellis decoders during one baud period in another predetermined sequence; and
4. receiver switching means for feeding n bits to the activated decoder and for collecting n plain text bits from the activated decoder.

5. The system of claim **4** wherein said transmitter switching means comprises a first transmitter switch for providing input bits to the activated trellis encoder, and a second transmitter switch for providing encoded bits from the activated trellis encoder to the signal encoding means.

6. The system of claim **5** wherein said signal encoding means comprises a quadrature amplitude modulator.

7. The system of claim **6** wherein said signal decoding means comprises a quadrature amplitude demodulator.

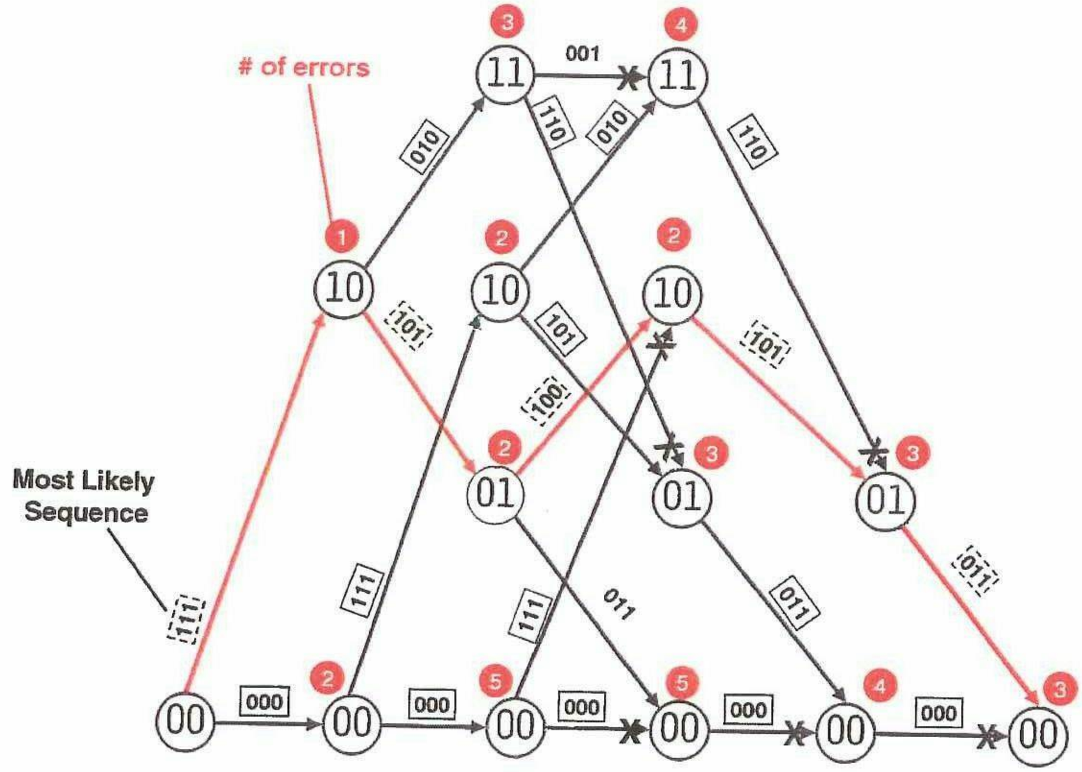
8. The system of claim **7** wherein there are k trellis encoders each trellis encoders including several delay elements for combining the bits received during said one baud periods with bits received during several preceding baud periods each preceding baud period being separated from the next baud period by $(k-1)$ D seconds where D is the duration of a period.

9. The system of claim **7** wherein said receiver switching means comprises a first receiver switch for feeding encoded bits to the activated decoders and a second receiver switch for collecting plain text bits from the activated decoders.

10. The system of claim **7** wherein each period has a time duration of D seconds and each encoder includes a delay element for delaying bits received during a baud period by D seconds.

11. The method of claim **3** further comprising providing a plurality of trellis decoders for sequentially decoding transmitted signals, each trellis decoder being activated sequentially for a baud period for deinterleaving said signals.

* * * * *



Received Sequence =	011	111	100	111	011
Most Likely Sequence =	111	101	100	101	011
Decoded Sequence =	1	0	1	0	0

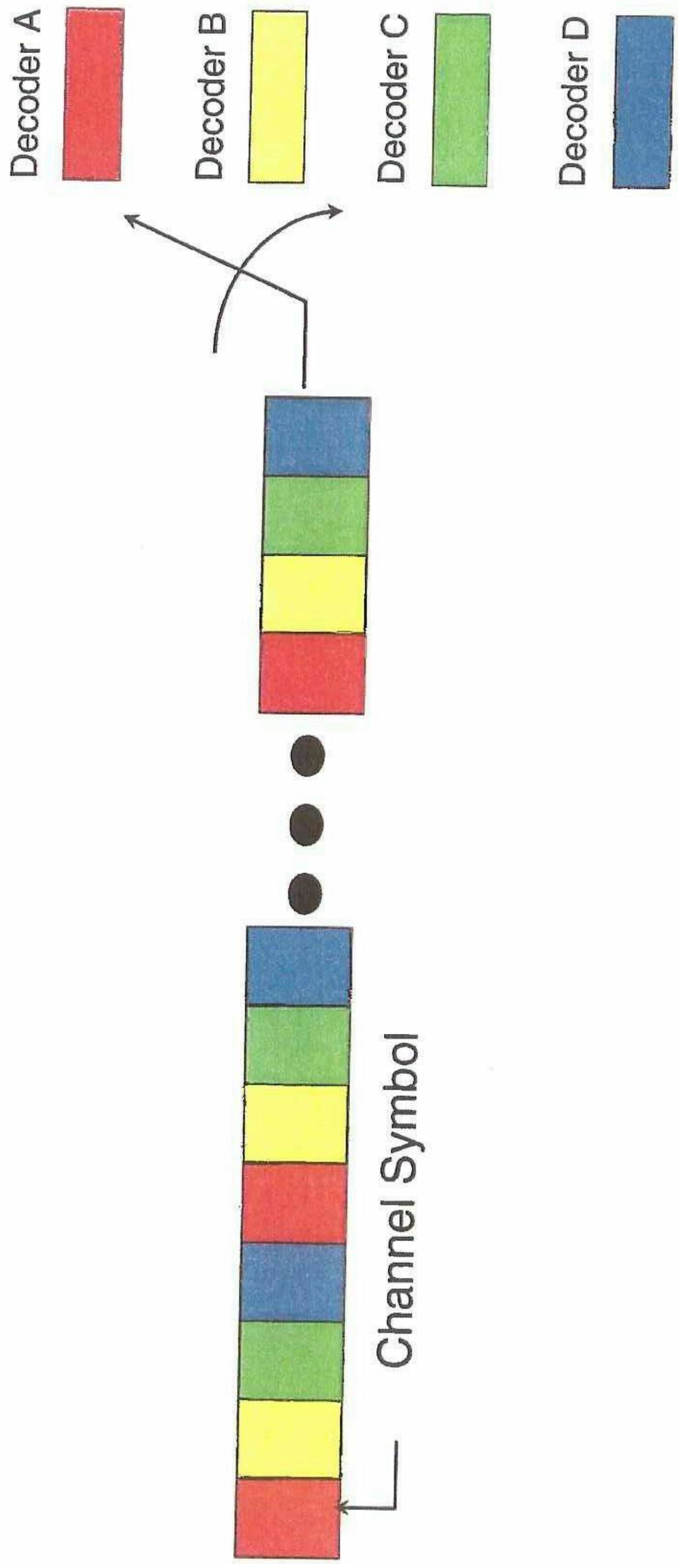
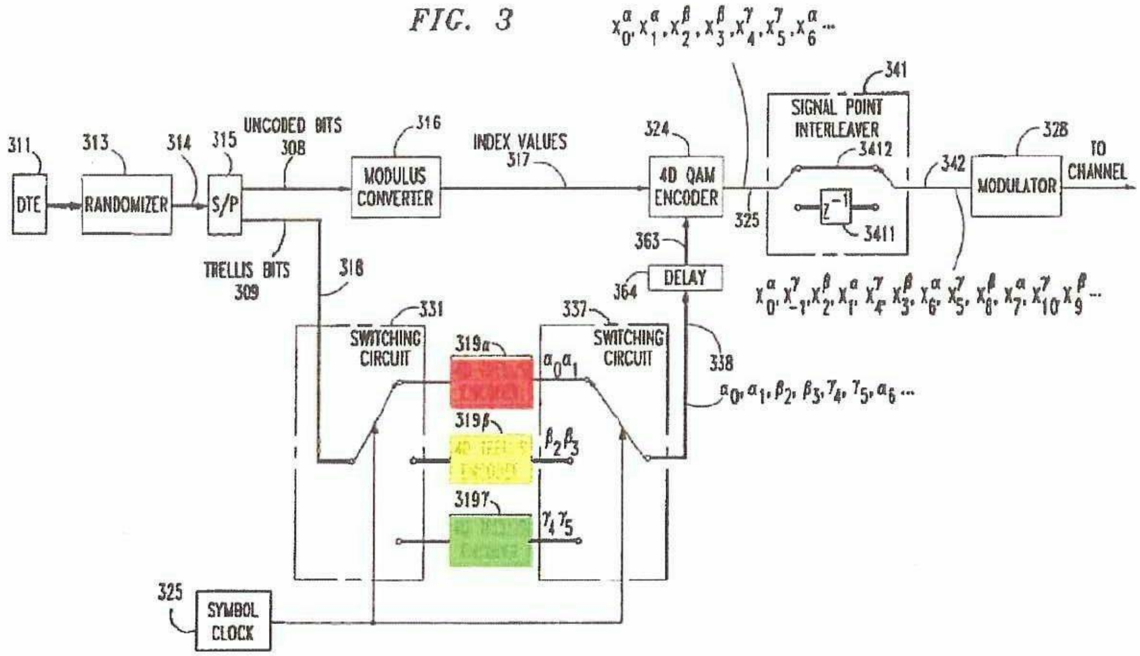
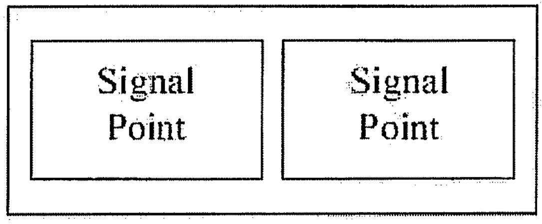

Decoder A
Decoder B
Decoder C
Decoder D
Channel Symbol

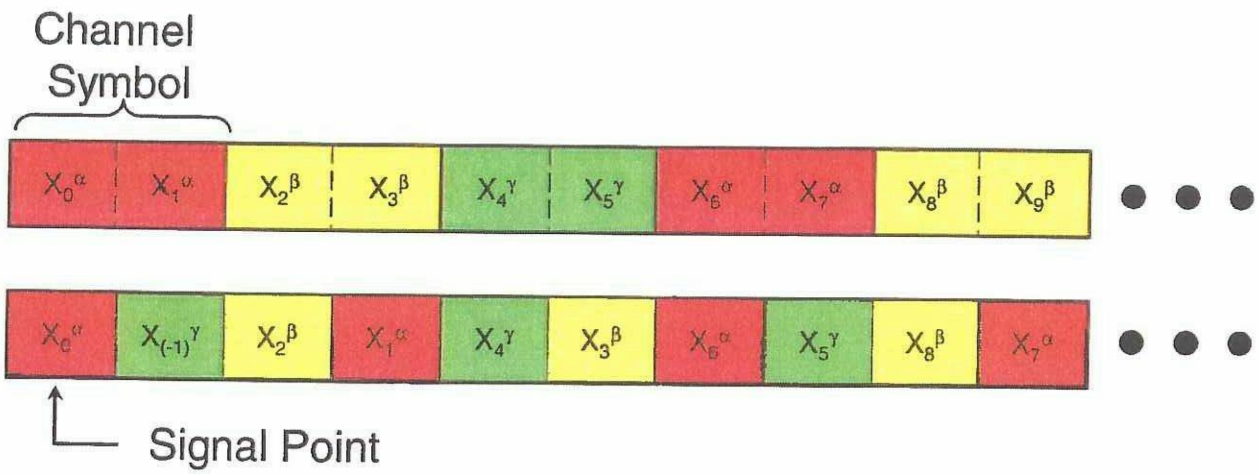
FIG. 3



DTE
RANDOMIZER
S/P
UNCODED BITS
308
MODULUS CONVERTER
INDEX VALUES
317
4D QAM ENCODER
SIGNAL POINT INTERLEAVER
MODULATOR
TO CHANNEL
TRELLIS BITS
309
DELAY
SWITCHING CIRCUIT
SWITCHING CIRCUIT
SYMBOL CLOCK
311
313
314
315
316
318
324
325
328
331
337
338
341
342
363
364
3411
3412
319α
319β
319γ



Trellis Encoded Channel Symbol


Channel Symbol
X_0^α X_1^α X_2^β X_3^β X_4^γ X_5^γ X_6^α X_7^α X_8^β X_9^β
X_0^α $X_{(-1)}^\gamma$ X_2^β X_1^α X_4^γ X_3^β X_6^α X_5^γ X_8^β X_7^α
Signal Point

TAB 3

Chart of Rembrandt's and All Other Parties' Proposed Constructions for U.S. Patent No. 5,243,627[1] And The Texas Court's Claim Constructions From *Rembrandt Technologies, L.P. v. Comcast Corp., et al.*[2]

'627 Claim Term	Texas Court's Construction	Rembrandt's Construction	All Other Parties' Construction
signal point	A value that is transmitted by a modulator in one signaling interval	A value that is transmitted by a modulator in one signaling interval.	A point on a 2-dimensional constellation having a pair of coordinates representing two components of a corresponding signal.
trellis encoded channel symbol	A set of one or more trellis encoded signal points that corresponds to a group of bits that is treated as a unit by an encoding system.	A set of one or more trellis encoded signal points that corresponds to a group of bits that is treated as a unit by an encoding system.	See "trellis encoded channel symbol … comprised of a plurality of signal points."
trellis encoded channel symbol … comprised of a plurality of signal points	No construction.	A set of two or more trellis encoded signal points that corresponds to a group of bits that is treated as a unit by an encoding system.	Two or more signal points all selected using the same group of parallel input bits as expanded once by a trellis encoder.
stream[] of trellis encoded channel symbols	No construction.	A sequence of trellis encoded channel symbols.	A sequence of trellis encoded channel symbols in which each symbol's signal points are adjacent.
distributed Viterbi decoder	A Viterbi decoder having multiple Viterbi decoding processing operating on separate portions of a stream of data to be decoded.	A Viterbi decoder having multiple Viterbi decoding processes operating on separate portions of a stream of data to be decoded.	See "distributed Viterbi decoder for recovering (to recover) said information from the deinterleaved signal points."
distributed Viterbi decoder for recovering (to recover) said information from the deinterleaved	No construction.	A Viterbi decoder having multiple Viterbi decoding processes operating on separate portions of a stream of deinterleaved signal points to recover the information encoded therein.	Multiple stage decoder in which each stage receives all of the deinterleaved signal points of a trellis encoded channel symbol before deciding their values together using the Viterbi algorithm.

[1] Extracted from the Parties' Joint Claim Construction Chart.

[2] Extracted from the June 5, 2007 Memorandum Opinion and Order in *Rembrandt Technologies, L.P. v. Comcast Corp. et al.*, Civil Action No. 2:05-CV-443(TJW) (E.D. Texas), a copy of which is attached as Exhibit 9.

'627 Claim Term	Texas Court's Construction	Rembrandt's Construction	All Other Parties' Construction
signal points			
interleaving the signal points of said generated channel symbols to form said stream of trellis encoded signal points	No construction.	To interleave signal points of trellis encoded channel symbols to form a stream of trellis encoded signal points.	Separating the adjacent signal points of each generated trellis encoded channel symbol using other signal points.
means for interleaving the signal points of said generated channel symbols to form said (a) stream of trellis encoded signal points	No construction.	Means plus function, to be construed per 35 U.S.C. § 112, ¶ 6 Function: interleaving the signal points of said generated channel symbols to form said stream of trellis encoded signal points. Structure: signal point interleaver and/or a switching circuit, or a processor programmed to interleave the signal points of the trellis encoded channel symbols.	Means plus function, to be construed per 35 U.S.C. § 112, ¶ 6 Function: interleaving the signal points of said generated channel symbols to form said stream of trellis encoded signal points. Structure: Signal Point Interleaver 341 including delay element 3411 or Signal Point Interleaver 641 including delay elements 6411, 6412 and 6413.
deinterleaving the interleaved signal points to recover said plurality of streams of trellis encoded channel symbols	No construction.	To reverse the process of interleaving performed in the transmitter to recover multiple streams of trellis encoded channel symbols from the interleaved signal points.	Restoring the adjacency of the separated signal points of each trellis encoded channel symbol to recover the two or more streams of trellis encoded channel symbols.
means for deinterleaving the interleaved signal points to recover said plurality of streams of trellis	Function: deinterleaving the interleaved signal points to recover said plurality of streams of trellis	Means plus function, to be construed per 35 U.S.C. § 112, ¶ 6 Function: deinterleaving the interleaved signal points to recover said plurality of streams of trellis	Means plus function, to be construed per 35 U.S.C. § 112, ¶ 6 Function: deinterleaving the interleaved signal points to recover said plurality of streams of trellis encoded channel symbols.

'627 Claim Term	Texas Court's Construction	Rembrandt's Construction	All Other Parties' Construction
encoded channel symbols	encoded channel symbols. Structure: signal point deinterleaver 441, or alternatively, signal point deinterleaver 741.	encoded channel symbols. Structure: signal point deinterleaver and/or a switching circuit, or a processor programmed to deinterleave the interleaved signal points.	Structure: Signal Point Deinterleaver 441 including delay element 4411 or Signal Point Deinterleaver 741 including delay elements 7411, 7412 and 7413.
receiver apparatus	No construction.	A device that receives a transmission signal.	A device that demodulates a received signal and recovers information in the form of a serial bit stream.
means for generating a plurality of streams of trellis encoded channel symbols in response to respective portions of said input information	No construction.	Means plus function, to be construed per 35 U.S.C. § 112, ¶ 6 Function: generating a plurality of streams of trellis encoded channel symbols in response to respective portions of said input information. Structure: a distributed trellis encoder that implements multiple trellis encoding processes operating on respective portions of input information.	Means plus function, to be construed per 35 U.S.C. § 112, ¶ 6 Function: generating a plurality of streams of trellis encoded channel symbols in response to respective portions of said input information. Structure: parallel trellis encoders and an encoder that generates signal points.

TAB 4

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B017

NEWTON'S TELECOM DICTIONARY

THE LOGIC OF MY DICTIONARY

by Harry Newton

Most technical dictionaries define terms tersely. As a result they leave you more confused. This dictionary is different. My definitions tell you what the term is, how it works, how you use it, what its benefits are and how it fits into the greater scheme of things.

This is a working dictionary. The idea is to use it every day. Salespeople tell me they include the definitions in proposals to customers. Users explain telecom things to their boss with my definitions. You can give it to your users, to your customers, to your boss. You can even give it to your kids to let them understand what you do.

HOW TO USE MY DICTIONARY

My definitions are in ASCII code order, NOT alphabetical order. ASCII is almost alphabetical order. But with some variations. Here is the order of the more common characters you'll find in this dictionary:

Blank Space	= ASCII 32	5	= ASCII 53
& (Ampersand)	= ASCII 38	6	= ASCII 54
Dash –	=ASCII 45	7	= ASCII 55
Period	= ASCII 46	8	= ASCII 56
/ (Forward slash)	= ASCII 47	9	= ASCII 57
0 (zero)	= ASCII 48	: (colon)	= ASCII 58
1	= ASCII 49	; (semi colon)	= ASCII 59
2	= ASCII 50	A (capital A)	= ASCII 65
3	= ASCII 51	Capital to lower case	= ASCII 90
4	= ASCII 52	a (lower case a)	= ASCII 97

I choose ASCII order over alphabetical order because ASCII is established. All computer sorting programs do sorts in ASCII order (unless you tell them otherwise). In contrast, when you do "alphabetical" sorts, no one seems to know which comes first: BACK SLASH or BACKSLASH, etc.

ON STYLE

All high-tech industries make up new words by joining words together, sometimes with a dash and sometimes without one. There are no rules, except with age and familiarity the dash tends to disappear. Sometimes it's just a matter of personal choice. Some people spell database as one word. Some as two, i.e. data base. I prefer it as one, since I've seen it that way most often.

within a given range.

REASSIGNMENT Here is an explanation by Bill Etling, a senior planner for GTE. "Under the assigned plant concept, a pair is dedicated from the central office to the subscriber home and maintained at that address, even when idle. The likelihood of such a pair being reused, thus eliminating a field visit and extra assignment work, more than makes up for lost revenue while the pair is vacant. In areas of high cable fills, such a pair, when vacant, is often used to fill an order at a different address. Reassignment quickly snowballs, generating many installation field visits and assignment changes, increasing paperwork and the chance of errors."

REBILLER See AGGREGATOR.

REBOOTING Repeating a Boot. Turning on or resetting the telephone system or the computer. The word derives from "boot-strapping." Starting from scratch. Pulling oneself up by one's own bootstraps. Booting a telephone system or a computer means starting it from scratch, usually by turning its AC power on. Rebooting a telephone system is done by simply turning it off, counting to ten and turning it back on again.

Rebooting is done to clear the volatile part of the telephone system's or computer's memory and its various processing and clock chips. You reboot typically when your PC "locks" inexplicably or when your telephone system does something you can't explain logically — like ring phones randomly or give strange error messages on the console. On a computer, "Lock" means that no matter which key or combination of keys you touch on your keyboard, you can't get your computer to do anything. In addition to "unlocking" your computer, you also reboot to clear RAM or RAM-resident programs. On an IBM or an IBM clone, rebooting is done by pressing the CONTROL, ALT and DELETE keys simultaneously. You can also reboot by pressing the reset button if your computer has one. (Not all do.)

You can reboot any computer by turning its power off, then turning it back on. This is usually not a good idea, since the surge of power that accompanies a computer being turned on and off will reduce the life of many of its electronic components. Some experts recommend leaving computers running full-time, though turning their hard disks off. They also recommend turning your screen off, or at least running a public domain program such as SCRNSAVE.COM or SCRN.COM which turn off your screen after several minutes of doing nothing (inactivity).

RECALL BUTTON Provides the flash function needed to operate many of the Dimension PBX features. Another word for FLASH BUTTON, as this button is called on other phones of other PBXs.

RECALL DIAL TONE A stutter or interrupted dial tone indicating to the extension user that the hookswitch flash has been properly used to gain access to system features.

RECALL KEY Used to get dial-tone or to transfer calls on a key system installed within a PBX. See also RECALL BUTTON.

RECEIVE INTERRUPTION The interruption of a transmission to a

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terminal to receive or send a higher priority message from the terminal.

RECEIVE ONLY RO. Describing operation of a device, usually a page printer, that can receive transmissions but cannot transmit.

RECEIVED LINE SIGNAL DETECTOR Modem interface signal defined in RS-232-C EIA interface which indicates to the attached data terminal equipment that it is receiving a signal from the distant modem.

RECEIVED SIGNAL LEVEL RSL. The strength of a radio signal received at the input to a radio receiver.

RECEIVER Any device which receives a transmission signal. 2. Any portion of a telecommunications device which decodes an encoded signal into its desired form. 3. The earpiece portion of a telephone handset, which converts an alternating electric current into sound waves, usually through an electromagnet moving a diaphragm. 4. An electronic component capable of collecting radio frequency broadcasts and reproducing them in their original audio and/or video form, e.g. a TV or radio receiver.

RECEIVER OFF-HOOK TONE The loud tone sent by the central office to tell the telephone user that his/her phone is off the hook.

RECEIVER SENSITIVITY The magnitude of the received signal necessary to produce objective BER or channel noise performance.

RECEIVING PERFORATOR REPERFORATOR. A telegraph instrument in which the received signals cause the code of the corresponding characters or functions to be punched in a tape.

RECENT CHANGE Changes to line and trunk translations in a stored program control switching machine that have not been merged with the permanent data base.

RECONFIGURATION A fancy word for rearranging equipment, features and options.

RECORD In a database, a record is a group of related data items treated as one unit of information — for example, your name, address and phone number. Each Record is made up of several fields. A field is simply your last name.

RECORD COMMUNICATIONS Any form of communication which produces a "written" record of the transmission. Teletypewriter and facsimile are examples or record communications. Companies such as RCA Globecom, ITT Worldcom, TRT and MCI, which provide international telex, are known as international record carriers. Before deregulation, that business was exceptionally profitable.

RECORD HEAD The electromagnetic device which magnetizes the surface of a magnetic recording — tape, disk, etc. — in proportion to an electrical signal.

RECORD LENGTH The number of bytes in a record. See RECORD.

RECORD LOCKING Think about an airline reservation. You call up. You want to change your reservation. While the airline has your record open, your travel agent calls up to change it. You change your reservation. Your

TAB 5

IN THE UNITED STATES DISTRICT COURT
FOR THE EASTERN DISTRICT OF TEXAS
MARSHALL DIVISION

REMBRANDT TECHNOLOGIES, L.P., Plaintiff,	§ § §	
v.	§	CIVIL ACTION NO. 2-05-CV-443 (TJW)
COMCAST CORP., ET AL., Defendants.	§ § § §	

MEMORANDUM OPINION AND ORDER

After considering the submissions and the arguments of counsel, the court issues the following order concerning the claim construction issues:

I. Introduction

Plaintiff Rembrandt Technologies, LP ("Rembrandt") accuses Comcast Corporation, Comcast Cable Communications, LLC, and Comcast of Plano, LP (collectively, "Comcast") of infringing United States Patent Nos. 5,719,858 ("the '858 patent") entitled "Time-Division Multiple-Access Method for Packet Transmission on Shared Synchronous Serial Buses," 4,937,819 ("the '819 patent") entitled "Time Orthogonal Multiple Virtual DCE for Use in Analog and Digital Networks," 5,852,631 ("the '631 patent") entitled "System and Method for Establishing Link Layer Parameters Based on Physical Layer Modulation," and 5,243,627 ("the '627 patent") entitled "Signal Point Interleaving Technique." This opinion resolves the parties' various claim construction disputes.

II. Background of the Technology

The '858 patent discloses a mechanism for allowing data sources to allocate, among themselves, time slots on a time division multiplexed ("TDM") bus. TDM allows multiple data sources to transmit data over a single network connection by dividing the network connection into

discrete time slots. Data sources generally transmit data only during their assigned time slot.

The '819 patent discloses an improved ranging mechanism for transmitting data from several remote units over a TDM network. Ranging is a way of measuring the transmission delay of data sent from a remote unit to a central node. By measuring this delay, the remote units can adjust the timing of their transmissions in order to reduce the empty times between transmissions.

The '631 patent addresses a manner to reduce the time required to establish a connection between two modems. Generally, when two modems attempt to communicate, they need to establish the two lowest "layers" of communication protocol, called the "physical layer" and the "link layer." The modems first negotiate the protocol to establish the "physical layer" connection and then negotiate the protocol to establish the "link layer" connection. The '631 patent discloses a technique for modems to use the "physical layer" negotiation to establish the "link layer" connection and, effectively, dispense with the "link layer" negotiations. This reduces the time necessary to establish a connection between the two modems.

The '627 patent discloses a method for correcting errors in digital data transmissions. In the prior art, one technique for correcting errors involved a "trellis encoder" in the transmitter and a "trellis" or "Viterbi" decoder in the receiver. In some circumstances, Viterbi decoders may fail to correct errors properly. The '627 patent discloses a combination of trellis encoding and signal point interleaving in an effort to improve error correction. Interleaving shuffles the data so that it is not in the same order as originally created. By using this technique, the system is able to guard against the situation where a number of consecutive transmitted bits become corrupted. As disclosed in the '627 patent, signal point interleaving helps to reduce errors within a single channel symbol. Bearing this background in mind, the court now addresses the claim construction issues.

III. General Principles Governing Claim Construction

"A claim in a patent provides the metes and bounds of the right which the patent confers on the patentee to exclude others from making, using or selling the protected invention." *Burke, Inc. v. Bruno Indep. Living Aids, Inc.*, 183 F.3d 1334, 1340 (Fed. Cir. 1999). Claim construction is an issue of law for the court to decide. *Markman v. Westview Instruments, Inc.*, 52 F.3d 967, 970-71 (Fed. Cir. 1995) (en banc), *aff'd*, 517 U.S. 370 (1996).

To ascertain the meaning of claims, the court looks to three primary sources: the claims, the specification, and the prosecution history. *Markman*, 52 F.3d at 979. Under the patent law, the specification must contain a written description of the invention that enables one of ordinary skill in the art to make and use the invention. A patent's claims must be read in view of the specification, of which they are a part. *Id.* For claim construction purposes, the description may act as a sort of dictionary, which explains the invention and may define terms used in the claims. *Id.* "One purpose for examining the specification is to determine if the patentee has limited the scope of the claims." *Watts v. XL Sys., Inc.*, 232 F.3d 877, 882 (Fed. Cir. 2000).

Nonetheless, it is the function of the claims, not the specification, to set forth the limits of the patentee's claims. Otherwise, there would be no need for claims. *SRI Int'l v. Matsushita Elec. Corp.*, 775 F.2d 1107, 1121 (Fed. Cir. 1985) (en banc). The patentee is free to be his own lexicographer, but any special definition given to a word must be clearly set forth in the specification. *Intellicall, Inc. v. Phonometrics*, 952 F.2d 1384, 1388 (Fed. Cir. 1992). And, although the specification may indicate that certain embodiments are preferred, particular embodiments appearing in the specification will not be read into the claims when the claim language is broader than the embodiments. *Electro Med. Sys., S.A. v. Cooper Life Sciences, Inc.*, 34 F.3d 1048, 1054

(Fed. Cir. 1994).

This court's claim construction decision must be informed by the Federal Circuit's decision in *Phillips v. AWH Corporation*, 415 F.3d 1303 (Fed. Cir. 2005) (en banc). In *Phillips*, the court set forth several guideposts that courts should follow when construing claims. In particular, the court reiterated that "the *claims* of a patent define the invention to which the patentee is entitled the right to exclude." 415 F.3d at 1312 (emphasis added) (quoting *Innova/Pure Water, Inc. v. Safari Water Filtration Systems, Inc.*, 381 F.3d 1111, 1115 (Fed. Cir. 2004)). To that end, the words used in a claim are generally given their ordinary and customary meaning. *Id.* The ordinary and customary meaning of a claim term "is the meaning that the term would have to a person of ordinary skill in the art in question at the time of the invention, i.e., as of the effective filing date of the patent application." *Id.* at 1313. This principle of patent law flows naturally from the recognition that inventors are usually persons who are skilled in the field of the invention. The patent is addressed to and intended to be read by others skilled in the particular art. *Id.*

The primacy of claim terms notwithstanding, *Phillips* made clear that "the person of ordinary skill in the art is deemed to read the claim term not only in the context of the particular claim in which the disputed term appears, but in the context of the entire patent, including the specification." *Id.* Although the claims themselves may provide guidance as to the meaning of particular terms, those terms are part of "a fully integrated written instrument." *Id.* at 1315 (*quoting Markman*, 52 F.3d at 978). Thus, the *Phillips* court emphasized the specification as being the primary basis for construing the claims. *Id.* at 1314-17. As the Supreme Court stated long ago, "in case of doubt or ambiguity it is proper in all cases to refer back to the descriptive portions of the specification to aid in solving the doubt or in ascertaining the true intent and meaning of the language employed in the

claims." *Bates v. Coe*, 98 U.S. 31, 38 (1878). In addressing the role of the specification, the *Phillips* court quoted with approval its earlier observations from *Renishaw PLC v. Marposs Societa' per Azioni*, 158 F.3d 1243, 1250 (Fed. Cir. 1998):

> Ultimately, the interpretation to be given a term can only be determined and confirmed with a full understanding of what the inventors actually invented and intended to envelop with the claim. The construction that stays true to the claim language and most naturally aligns with the patent's description of the invention will be, in the end, the correct construction.

Consequently, *Phillips* emphasized the important role the specification plays in the claim construction process.

The prosecution history also continues to play an important role in claim interpretation. The prosecution history helps to demonstrate how the inventor and the PTO understood the patent. *Phillips*, 415 F.3d at 1317. Because the file history, however, "represents an ongoing negotiation between the PTO and the applicant," it may lack the clarity of the specification and thus be less useful in claim construction proceedings. *Id.* Nevertheless, the prosecution history is intrinsic evidence. That evidence is relevant to the determination of how the inventor understood the invention and whether the inventor limited the invention during prosecution by narrowing the scope of the claims.

Phillips rejected any claim construction approach that sacrificed the intrinsic record in favor of extrinsic evidence, such as dictionary definitions or expert testimony. The *en banc* court condemned the suggestion made by *Texas Digital Systems, Inc. v. Telegenix, Inc.*, 308 F.3d 1193 (Fed. Cir. 2002), that a court should discern the ordinary meaning of the claim terms (through dictionaries or otherwise) before resorting to the specification for certain limited purposes. *Id.* at 1319-24. The approach suggested by *Texas Digital*–the assignment of a limited role to the

specification–was rejected as inconsistent with decisions holding the specification to be the best guide to the meaning of a disputed term. *Id.* at 1320-21. According to *Phillips*, reliance on dictionary definitions at the expense of the specification had the effect of "focus[ing] the inquiry on the abstract meaning of words rather than on the meaning of the claim terms within the context of the patent." *Id.* at 1321. *Phillips* emphasized that the patent system is based on the proposition that the claims cover only the invented subject matter. *Id.* What is described in the claims flows from the statutory requirement imposed on the patentee to describe and particularly claim what he or she has invented. *Id.* The definitions found in dictionaries, however, often flow from the editors' objective of assembling all of the possible definitions for a word. *Id.* at 1321-22.

Phillips does not preclude all uses of dictionaries in claim construction proceedings. Instead, the court assigned dictionaries a role subordinate to the intrinsic record. In doing so, the court emphasized that claim construction issues are not resolved by any magic formula. The court did not impose any particular sequence of steps for a court to follow when it considers disputed claim language. *Id.* at 1323-25. Rather, *Phillips* held that a court must attach the appropriate weight to the intrinsic sources offered in support of a proposed claim construction, bearing in mind the general rule that the claims measure the scope of the patent grant. The court now turns to a discussion of the disputed claim terms.

IV. Terms in Dispute

A. '858 Patent

1. "time-division multiplexed bus"

The first term for construction is "time-division multiplexed bus." The plaintiff argues that the term means "a bus having a bandwidth partitioned into regular time slots, that is shared by two

or more sources of data by limiting each source's transmission opportunities to discrete intervals of time." The defendants argue that the term means "a group of one or more conductors that is shared among several users by allowing each user to use the bus for a given period of time in a defined, repeated sequence." The parties appear to agree that a bus allows different sources of data to share bandwidth. The principal dispute is whether the transmission sequence must be a "defined, repeated sequence."

The defendants cite to portions of the specifications that refer to repeated frames for a fixed portion of the TDM bandwidth. *See* '858 patent, 4:56-57, 5:21-6:5. In addition, the defendants point to extrinsic evidence. *See* The New IEEE Standard Dictionary of Electrical and Electronic Terms, at 1377 (5th ed. 1993). The plaintiff argues, however, that by limiting the transmission sequence to be a "defined, repeated sequence," the defendants' construction would exclude a preferred embodiment where data sources are skipped when they have no data to send. *See* '858 patent, Fig. 6, 7:25-9:15.

The court agrees that the patent discloses an embodiment where certain data sources are skipped when they have no data to send. For this reason, the "defined, repeated sequence" more appropriately describes the frames for the fixed portion of the TDM bandwidth. So viewed, the court agrees that the frames are arranged in a "defined, repeated sequence." Accordingly, the court construes the term to mean "a bus having a bandwidth partitioned into a defined, repeated sequence of time slots, that is shared by two or more sources of data by limiting each source's transmission opportunities to discrete intervals of time."

2. "packet data" and "synchronous data"

The plaintiff proposes that "packet data" means "variable bit rate data" and "synchronous

data" means "constant bit rate data." The defendants propose that "packet data" means "data that is transmitted in packets" and "synchronous data" means "constant bit rate data that is not transmitted in packets." Both parties appear to agree that "synchronous data" refers to constant bit rate data. The dispute is whether "packet data" can also include constant bit rate data.

The specification defines these terms:

> The present invention relates to data communications, and more particularly to communications systems that have channelized network access, and may transport both synchronous data and variable-bit-rate data such as frame relay data (hereafter referred to as packet data), in a time-division multiplexed format.

'858 patent, 1:8-11.

Contrary to the defendants' arguments, the patent defines "variable bit rate data" as "packet data," and the court adopts this construction. Moreover, the court defines "synchronous data" as "constant bit rate data."

3. "portion of the [predefined] bandwidth"

The next term is "portion of the [predefined] bandwidth." The plaintiff argues that this term means "one or more time slots in a TDM frame assigned to a group of data sources." The defendants contend that the term means "the part, but less than all, of the data transfer capacity of the bus that is allotted either to packet data or to synchronous data." The dispute is whether the term "portion" can include the full bandwidth or whether it is limited to less than the full bandwidth.

The intrinsic evidence does not support a construction which departs from the ordinary meaning of "portion." As argued by the defendants, the purpose of the invention was to facilitate the transmission of both packet and synchronous data over the TDM bus. *See* '858 patent, 2:42-45 ("I have realized an alternative approach to the design of TDM-based equipment that supports *both*

synchronous data and packet data and, in addition, provides an efficient substrate for packet handling.")(emphasis added); Figs. 3, 5 (depicting the allocation of a part of the TDM bus to the multiple access packet channel). As used in the patent, "portion" means less than all. Accordingly, the court construes the term to mean "the part, but less than all, of the data transfer capacity of the bus that is assigned to a group of data sources."

4. "predefined bandwidth"

The plaintiff contends that this term means "a TDM frame with a fixed number of time slots." The defendants argue that this term means "data transfer capacity fixed in advance of operation." Although the plaintiff cites to the abstract, the defendants' proposed construction embraces the definitions of "predefined" and "bandwidth" as used in the claims. The court adopts the defendants' proposed construction.

5. "distributed packet manager"

The next term is "distributed packet manager." The plaintiff argues that this term means "a device, process or algorithm that is located within each packet data source, that controls how the packet data source accesses a portion of the bandwidth assigned to the packet data." The defendants propose "a decentralized mechanism that performs all the functions required to aggregate and synchronize packet data to the time-division multiplexed bus and to prevent packet collisions." The defendants' proposed construction limits the claim by requiring, essentially, an entirely decentralized mechanism for performing "all" of the functions required to aggregate and synchronize packet data to the bus. In addition, the defendants' construction requires the packet manager to prevent packet collisions.

The court is not persuaded that either limitation is appropriate. The specification does not

require the elimination of all of the central control functions. Moreover, the doctrine of claim differentiation counsels against the requirement that the packet manager prevent packet collisions. Claim 9 recites "only one of the plurality of packet data sources accesses the . . . predefined bandwidth at a time" whereas claim 7 does not require that "only one" packet data source can access the bus at a time. Claim 9 thus expresses the concept of preventing packet collisions by allowing only one of the packet data sources to access the predefined bandwidth at a time. The defendants' proposed construction would incorporate limitations from the preferred embodiment that are not required by the language of the claims. As such, the court construes the term to mean "a device, process or algorithm located within each packet data source, that controls how the packet data source accesses the time-division multiplexed bus."

6. "allocate access to the allotted bandwidth among said packet data sources"[1]

The plaintiff defines this term to mean "controlling access by each of the packet data sources to the portion of bandwidth previously assigned to packet data." The defendants' proposed construction is "apportion to each of the packet data sources sole permission to attempt to transmit in the portion of bandwidth previously assigned to packet data." The dispute is whether "allocating/controlling access" requires some sort of permission to transmit in a given time period. The defendants argue that packet sources do not contend for bandwidth by transmitting simultaneously, but by "capturing" permission to use the MAPC. *See* '858 patent, 6:53-7:8. The plaintiff argues that the defendants are attempting to limit the construction to a preferred

[1] Corresponding phrases include "allocate access to the second portion of the predefined bandwidth among said packet data sources" and "controlling [the] access by said packet data sources to the allocated portion of the bandwidth."

embodiment. The court agrees and concludes the term means "controlling access by each of the packet data sources to the portion of bandwidth previously assigned to packet data."

7. "network access manager/module"

The plaintiff contends that this term means "a device, process or algorithm for controlling the assignment of synchronous and packet data portions on a TDM bus, and for passing data between the bus and a network." The defendants argue that the court should not construe this term. They add that the plaintiff's proposed construction is confusing because it describes functions from the "distributed packet manager." The plaintiff, on the other hand, contends that the specification discusses two functions of the network access manager and that a construction consistent with the specification would help the jury understand the functions of the network access manager.

A review of the specification demonstrates the propriety of the plaintiff's proposal. The specification states that the network access module "controls time-slot allocation among the synchronous modules and the packet modules." '858 patent, 5:12-13. The network access module also "provides the interface between the TDM bus and network facility." '858 patent, 3:46-47. The plaintiff's proposed construction captures a definition of the network access manager in essentially these terms. The court construes the term to mean "a device, process or algorithm for controlling the assignment of synchronous and packet data portions on a TDM bus, and for passing data between the bus and a network."

B. '819 Patent

1. "application program"

Claim 1 of the '819 patent requires a master unit communicating with a plurality of remote units. The remote units must be executing "application programs." The parties dispute the

construction of this term. The plaintiff defines the term to mean "a computer program or process." The defendants propose "a program designed to assist in the performance of a specific end-user task (*e.g.*, word processing, accounting, or inventory management) in contrast to a program designed to perform management of or maintenance work on the system or system components."

The ordinary meaning of the term "application program" is software that performs tasks for an end-user. Despite the parties' arguments for different constructions, the court discerns nothing in the patent or the prosecution history that would vary the ordinary meaning for this term. As such, the court defines "application program" to mean "software that performs tasks for an end-user."

2. "time slot assigned to each of said application programs"

Claim 1 also requires that the remote units receive messages from the master unit and respond in a "time slot assigned to each of said application programs." The parties' dispute concerns whether the "assignment" function must occur at initialization of the application program (the defendants' construction) or whether it may occur at any time. The plaintiff argues that the defendants' construction is inconsistent with the disclosure because the remote units can request additional time slots during data transmission, which is after initialization. *See* '819 patent, 2:18-26, 3:7-11. The defendants argue that the specification repeatedly discloses time slots assigned to applications at initialization. *See* '819 patent, 2:46-49, 5:42-43, Fig. 6, Fig. 7.

Although the specification refers to the assignment of time slots during initialization, there is nothing in the patent that requires the claims to be limited in this manner. The court construes "time slot" to mean "an interval of time during which data from an application program is transmitted." All other terms have their plain and ordinary meaning.

3. "dividing a period of a clock in said master unit into a number of subframes, dividing each subframes into a number of slots, each corresponding to transmission times for one of said remote units, and assigning a slot to each of said application programs"

This phrase appears in claim 14 of the '819 patent. The defendants contend that the phrase needs clarification because it is not clear what "each" refers to. They also urge that the file history indicates a disclaimer that messages sent from the master unit to the remote units are not packetized. The court has reviewed the cited portions of the prosecution history and is not persuaded that the patentee limited the claim to outbound non-packetized messages from the master unit. The court therefore construes "each corresponding to transmission times" to mean "each subframe corresponding to transmission times." All other terms have their plain and ordinary meaning.

4. "master network timing means"

Claim 1 requires a master unit with a master network timing "means." In relevant part, claim 1 states "said master unit including a master network timing means with a period which is divided into a plurality of subframes, wherein each subframe is divided into said time slots, and each of said time slots is used as an interval in which one of said application programs . . . ." '819 patent, claim 1. The parties debate whether this limitation is a means-plus-function limitation.

Use of the word "means" invokes a presumption that the claim is governed by 35 U.S.C. § 112 ¶ 6. The plaintiff, however, correctly observes that the limitation does not recite any function performed by the means and, as such, is outside the scope of § 112 ¶ 6. *Sage Products, Inc. v. Devon Industries, Inc.*, 126 F.3d 1420, 1427 (Fed. Cir. 1997).

Although the phrase is not a means-plus-function limitation, the plaintiff suggests that the court should construe the "timing means" limitation. The plaintiff proposes a construction of "a

clock for determining network timing or for delineating time into time slots." Although the defendants do not propose an alternative construction, they disagree that a clock determines what the period shall be and how the period should divide into subframes and time slots. The defendants instead argue that the period, subframes, and time slots are determined by the network timing and control processor. *See* '819 patent, 3:1-3. The plaintiff, on the other hand, argues that the description of "master network clock" in the specification matches the language of the claim. *See* '819 patent, 6:37-39, 7:38-39.

Because the term is not governed by § 112 ¶ 6, it is improper to limit the term to the structures described in the specification. The language of this claim limitation needs no further construction, and the court rejects the plaintiff's attempt to limit the term to the master network clock recited in the patent.

5. "ranging means"

Like the previous term, the parties dispute whether the term is a means-plus-function limitation. In relevant part, claim 1, states:

> said master unit including ranging means communicating with said master network timing means *wherein a transmission time between said master unit and each of said respective remote units is calculated and transmitted* from said master unit to each of said respective remote units, each of said respective remote units using said transmission time to adjust initiation of said time slots.

'819 patent, claim 1 (emphasis added).

Again, the plaintiff urges that there is no recited function performed by the recited means. According to the plaintiff, the limitations in the claim refer to the master unit and not to the ranging means.

The court disagrees. The plaintiff has not overcome the presumption that this term is drafted

according to § 112 ¶ 6. What distinguishes this term from the previous one is the inclusion of the functional language "wherein a transmission time between said master unit and each of said respective remote units is calculated and transmitted." This language, coupled with the use of the word "means," counsels the court to apply § 112 ¶ 6.

The court construes the function to mean "calculating and transmitting to each remote unit the time it takes to transmit between the master and that remote unit." The corresponding structure is the network timing and control processor 12, the ranging and network initialization generator 20, and ranging receiver 32.

6. "reservation request generator" and "reservation request processor"

The plaintiff proposes that "reservation request generator" means "a device or process that adds to a message a request for additional time slots" and that "reservation request processor" means "a device or process for receiving and processing requests for additional time slots from a reservation request generator." The defendants contend that the terms do not need construction. However, if the court decides that the terms require construction, the defendants propose that "reservation request generator" means "a device or process that sets reservation bits in a message to request additional time slots" and "reservation request processor" means "a device or process that can grant a request from a remote unit for more time slots in order for the remote unit to transmit a longer message."

The defendants' proposals improperly limit the terms to preferred embodiments. The court adopts the plaintiff's proposed constructions for both terms.

7. "priority bit"

The term "priority bit" appears in claim 11 of the '819 patent. The issue is whether the priority bit is limited to defining the importance of remote units or whether it can define the

importance of other things, such as an application. By limiting the construction to the importance of remote units, the defendants attempt to limit the construction to a preferred embodiment. The language of the claim is entitled to a broader construction, and the court construes this term to mean "a bit that is used to convey the relative importance of the communication."

C. '631 Patent

1. "physical layer" and "physical layer modulation"

The court concludes that the term "physical layer" means "the lowest layer of the Open Systems Interconnect (OSI) seven layer model, concerned with establishing the mechanical, electrical, functional, and procedural connection between two modems." Similarly, "physical layer modulation" means "a protocol that is concerned with establishing the mechanical, electrical, functional, and procedural connection between two modems."

2. "negotiated physical layer modulation"

The parties are in agreement that this term means "a physical layer modulation selected by a process permitting two modems supporting different layer modulations to agree on a common supported physical layer modulation after exchanging information at run time." The court accordingly adopts this construction.

3. "link layer"

As expressed at oral argument, it appears that the parties are in substantial agreement on the construction of this term. They agree that the link layer is the second lowest layer of the OSI seven layer model and that it performs error checking functions. The main issues appear to be whether error correction is limited to frame transmission and/or whether the plaintiff's construction includes error correction at the physical layer. The defendants also argue that one of ordinary skill in the art

would understand that retransmission of messages is the way to correct transmission errors.

The court has considered the briefs and the arguments of the parties in light of the intrinsic record. The court construes the term "link layer" to mean "the second lowest layer of the Open Systems Interconnect (OSI) seven layer model, providing the functional and procedural means to transfer data between modems, and to detect and correct errors."

4. "means for establishing a physical layer connection between said calling and said answer modems, wherein said physical layer connection is based on a negotiated physical layer modulation chosen from said first and second physical layer modulations"

The parties agree that this phrase is drafted in means-plus-function form. They also agree that the function is "establishing a physical layer connection based on a negotiated physical layer modulation." The parties disagree on the structure. Although the parties agree that a control processor or digital signal processor chip must be able to execute the algorithms described in Fig.4-9, they disagree over whether the processor may be capable of executing each algorithm standing alone (the plaintiff's argument) or whether the processor must be capable of executing pairs of algorithms (the defendant's argument).

To establish a connection, both a calling and answering modem must perform an algorithm. The specification discloses only two alternative pairs of interdependent algorithms (Fig. 4 with Fig. 5, and Fig. 6 with Fig. 7), and either pair must run to perform the claimed function of establishing a connection. This is because establishing a connection requires both a calling and an answering modem. The corresponding structure includes a processor running the algorithms shown in Figs. 4 and 5 or, alternatively, Figs. 6 and 7.

5. "means for establishing said link layer connection based upon said negotiated physical layer modulation"

The parties agree that the function is "establishing the link layer connection based upon the negotiated physical layer." The parties disagree on the structure.

The plaintiff argues that the only structure necessary to perform this function is programmable hardware (*i.e.*, a control processor or digital signal processor chip) configured to perform the function set forth in Fig. 8. The defendants argue that Fig. 8 is purely a functional diagram and no algorithm has been disclosed. According to the defendants, the claim is invalid as indefinite. In reply, the plaintiff argues that the court should not entertain the indefiniteness argument because the defendants failed to disclose it in their Invalidity Contentions.

The timing of the argument notwithstanding, this court's role is to construe the claims. That task implicates a question of law. As a result, the court has attempted, unsuccessfully, to identify any disclosed corresponding structure. At this time, however, the court reserves construction of this phrase and invites the plaintiff to submit supplemental briefing on this issue within ten (10) days from the date of this order. The briefing shall respond to the defendants' argument that *WMS Gaming Inc. v. Int'l Game Tech.*, 184 F.3d 1339, 1349 (Fed. Cir. 1999) controls this issue and that the specification fails to disclose corresponding structure in the form of an algorithm. Such briefing shall be limited to ten (10) pages. This procedure is sufficient to cure any prejudice resulting from the failure to timely raise the indefiniteness argument.

6. "means for presetting link layer parameters of said link layer connection to pre-defined settings based on said negotiated physical layer modulation"

For essentially the reasons expressed in the preceding discussion, the court reserves construction of this phrase pending receipt of supplemental briefing. The plaintiff shall include any

argument on this term within the page limits allotted to it.

D. '627 Patent

1. "trellis encoded channel symbol"

The plaintiff argues that this term means "a set of one or more trellis encoded signal points that corresponds to a group of bits that is treated as a unit by an encoding system." The defendants propose a construction that defines the term to mean "the output of a mapper that is generated using the output(s) of a single state transition of a trellis encoder." The principal dispute is whether the output is limited to a "single state transition."

The plaintiff argues that a channel symbol is the output of the trellis encoding process corresponding to a group of input bits or "parallel bits." *See* '627 patent, 2:61-65, 3:53-58. The plaintiff observes that the trellis encoded channel symbol is derived from a "succession of N outputs from the trellis encoder . . . ." '627 patent, 4:20. According to the plaintiff, multiple outputs correspond to a separate state change and, therefore, a single state transition cannot be a limitation.

The defendants argue that a trellis state transition occurs only when the encoder has moved on to the next symbol. According to the defendants, the "succession of outputs" referenced by the plaintiff refers to subset identifiers which are generated in parallel while the encoder operates on the data. Subset identifiers collectively determine the trellis encoded symbol. The defendants argue that nothing in the intrinsic evidence suggests that these outputs are the result of multiple state changes in the trellis encoder.

The plaintiff's argument is correct. A trellis encoder working on a multiple bit word produces a succession of subset identifiers which collectively make up the trellis encoded symbol. *See* '627 patent, 5:1-30. The subset identifiers are then supplied to another encoder, *e.g.*, a four-

dimensional QAM encoder, which outputs a stream of signal points comprised of interleaved streams of trellis encoded channel symbols. *Id.* The plaintiff's construction of this term is correct, and the court adopts it.

2. "signal point"

The plaintiff proposes that the term "signal point" means "a value that is transmitted by a modulator in one signaling interval." The defendants propose "a single mapped point in a signal constellation." The defendants support this construction by arguing that one of ordinary skill in the art would understand the term "signal point" to refer to a mapped point in a signal constellation. The defendants also contend that signal constellations include many different dimensionalities. In addition, the defendants argue that a "signal point" is not actually transmitted; instead, a waveform representing the bits values associated with the signal point is transmitted.

The plaintiff responds by arguing that the '627 patent does not mention "mapping." The plaintiff also points to the specification which states that "signal points are thereupon communicated over the channel." '627 patent, 4:1-3.

The court agrees with the plaintiff that the intrinsic evidence fails to require a signal point "mapped" in a constellation. Based on the cited portion of the specification, the court agrees that the proper construction for this term is "a value that is transmitted by a modulator in one signaling interval."

3. "distributed Viterbi decoder"

The process of Viterbi decoding is used to decode a trellis encoded signal. Claims 9 and 19 of the '627 patent require a "distributed Viterbi decoder." The plaintiff proposes that this term means "a Viterbi decoder having multiple Viterbi decoding processes operating on separate portions

of a stream of data to be decoded." The defendants argue that the term means "two or more Viterbi decoders operating in round-robin fashion on separate portions of a stream of encoded data." The issue is whether there needs to be more than one Viterbi decoder operating in round-robin fashion.

The defendants point to the specification which shows separate Viterbi decoders that are accessed sequentially. '627 patent, Fig. 4, 3:13-20. The plaintiff, on the other hand, contends that the defendants are attempting to limit the term to a preferred embodiment. According to the plaintiff, a distributed Viterbi decoder can be implemented as a single Viterbi decoder that emulates through software the function of multiple devices. The relevant passage from the specification supports the plaintiff's argument. '627 patent, 9:61-66 ("multiple trellis encoders and decoders can be realized using a single program routine which, through the mechanism of indirect addressing of multiple arrays within memory, serves to provide the functions of each of the multiple devices.").

In light of this passage from the specification, the court is persuaded that the plaintiff's construction is correct. The court concludes that this term means "a Viterbi decoder having multiple Viterbi decoding processes operating on separate portions of a stream of data to be decoded."

4. "means for deinterleaving the interleaved signal points to recover said plurality of streams of trellis encoded channel symbols"

Both parties agree that this is a means-plus-function claim to be construed pursuant to § 112 ¶ 6. The court concludes that the claimed function is "deinterleaving the interleaved signal points to recover said plurality of streams of trellis encoded channel symbols." The corresponding structure that is clearly linked to the claimed function is the signal point deinterleaver 441 or, alternatively, signal point deinterleaver 741. *See* '627 patent, Figs. 4 and 7; 5:67-68; 9:45-51.

V. Conclusion

The court adopts the above constructions for the terms in need of construction. The parties are ordered that they may not refer, directly or indirectly, to each other's claim construction positions in the presence of the jury. Likewise, the parties are ordered to refrain from mentioning any portion of this opinion, other than the actual definitions adopted by the court, in the presence of the jury. Any reference to claim construction proceedings is limited to informing the jury of the definitions adopted by the court.

SIGNED this 5th day of June, 2007.

Charles Everingham IV

CHARLES EVERINGHAM IV
UNITED STATES MAGISTRATE JUDGE

TAB 6

IN THE UNITED STATES DISTRICT COURT

FOR THE DISTRICT OF DELAWARE

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In re:

REMBRANDT TECHNOLOGIES, LP	MDL Docket No.07-md-1848(GMS)
PATENT LITIGATION	CHIEF JUDGE GREGORY M. SLEET

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June 23, 2008

10:06 a.m.

VIDEOTAPED DEPOSITION of RICHARD D. GITLIN, taken by Attorneys for Rembrandt Technologies, pursuant to Claim Construction, at the offices of Weil Gotshal & Manges, 757 Fifth Avenue, New York, New York, before Amy Klein, a Shorthand Reporter and Notary Public within and for the State of New York.

- Gitlin -

A. So a signal point is a point in this two-dimensional space, so it has X and Y coordinates.

Q. What about a point in amplitude modulation figure?

A. In Ungerboek's paper.

Q. Yes, in Ungerboek's paper.

A. That is one-dimensional, so it has amplitude.

Q. So Ungerboek's paper illustrates a one-dimensional signal point in figure 1, under "Amplitude Modulation"?

A. Figure 1, the upper left-hand corner, is an example of amplitude modulation.

Q. And the point on that constellation is a one-dimensional signal point?

A. Yes.

MR. KOLMYKOV: Could we --

THE VIDEO OPERATOR: This completes Tape Number 1. The time is 11:52 a.m., and we're going off the record.

(A recess was taken.)

THE VIDEO OPERATOR: This is Tape Number 2. The time is 12:00 p.m., and we're back on the

A. I'm not an expert in that. I think there were other issues related to range, and they use a pilot tone.

I recall there was a debate between QAM and VSB and, as these debates go, VSB won. And that's a different circumstance than the wire line systems in the context of Ungerboek had been dealing with, and the Betts' patent addresses.

I would say, to be fair, that's about the only system, commercial system, I know that could be called a one-dimensional system since the -- around 1980.

Q. So since ATSE does use a one-dimensional system, it is possible to use a one-dimensional system?

A. Yes.

Q. Even though according to your opinion it's not as good as the QAM?

A. In the context of the environments that I'm intimately familiar with. I'm not an expert on over-the-air television transmission.

Q. Can trellis encoding be implemented with one-dimensional signals?

A. Yes. Yes.

- Gitlin -

manipulates the signals -- they are already in digital form.

Q. So trellis encoding and the bit mapping into signal points can all be implemented in software?

A. I wouldn't -- you drew a distinction which I don't accept. Trellis encoding includes the mapping into the signal points.

Q. And this bit mapping together with the encoding or expansion of the input bits can be performed in software?

A. It depends on the rates in which you're processing. So if you're processing at a rate where the chip or the ASIC can do it, you can do this all in one device.

But if you were operating at a very, very high bit rate, it might not be possible to do this in one device.

Q. Can you give me an example of a bit rate that a single device cannot handle?

A. Well, I can make up a very large number.

Suppose I wanted to build 100 gigabit system.

MR. TROPP: Just out of curiosity, we're

still on his declaration in some form?

MR. KOLMYKOV: Yeah.

MR. TROPP: Yeah? I'm having trouble understanding the connection. But on your representation that's where we are, go ahead.

MR. KOLMYKOV: I'm continuing with his description of trellis encoding and what it means.

MR. TROPP: I'm not sure you're continuing with his description. But on your representation that that's where you are, go ahead.

BY MR. KOLMYKOV:

Q. Well, let's refer to figure 3 of the '627 patent.

A. Just a minute.

Q. Do you see a QAM encoder designated as 324?

A. Yes. Yes.

Q. And you see the 4D trellis encoders: 319 alpha, 319 beta, 319 gamma?

A. I see what he labels as trellis encoders.

Q. So my question to you is whether the unit 324 and the units 319 alpha, beta and gamma can be implemented together in one device?

- Gitlin -

A. As I said, it depends upon the speed of application. You -- one of the tenets of communication systems to get cost-conscious designs is to combine elements.

So in principle, almost all, especially digital elements, could be combined. Assuming the processor has enough speed.

Q. All right, thank you.

During your discussion of the trellis encoding you mentioned that a trellis encoded channel symbol is generated to one expansion of the input bits; is that correct?

A. Yes.

Q. Is it fair to say that a channel symbol is a group of bits?

A. A channel -- in the context of the panel, or --

Q. In general.

A. It's -- you know, it's a word that's used in multiple contexts. So without saying specifically what are you talking about, it could have several meanings.

My declaration interprets it in the context of the patent.

where one state transition leads to more than one expansion?

A. That's not what -- the way a trellis coder operates. I am not aware of anything.

I think I explained many times, trellis encoder cycles through one state transition, produces an expanded set of bits. That's the way a trellis coder operates.

Q. Can it produce several expanded group of bits in one cycle of the machine?

A. It produces one expanded set of bits that, then, could be mapped -- if it's 2N-dimensional those bits will then be mapped over N signaling intervals. That's the way -- that's the way a multi-dimensional trellis coder works.

Q. And when you produce this expanded group of bits, could that expansion add more than one bit?

A. It's not the way that I typically think of it, but in Wei's last paragraph he suggests that you could.

Q. Is it your opinion that it is possible?

A. To do what?

Q. Do you have an opinion as to whether

- Gitlin -

MR. TROPP: If four attorneys represented the same party you would be perhaps correct. But here we each have our own separate interests and we're entitled to make our own separate records.

MR. KOLMYKOV: I'll leave that issue open to discussion.

BY MR. KOLMYKOV:

Q. Let's turn to column 8, pages 47 to 50, of the '627 patent.

MR. TROPP: I'm sorry, what columns of the '627?

MR. KOLMYKOV: 47 through 50.

MR. TROPP: Thank you.

Q. I will read it into the record.

"Without having received all of the signal points of a channel symbol, one cannot take advantage of the accumulated path metric information, but, rather must rely on the so-called raw sliced values, which is less accurate."

Doesn't this statement imply that the path metric is already being accumulated upon reception of a single signal point?

A. You can build suboptimum receivers in

many ways. As he says, "which is less accurate." You can build lots of less accurate receivers. He makes that comment. Okay.

Q. So it is possible to build a receiver that will process one signal point at a time?

MR. TROPP: Objection.

A. It's always possible to build a receiver. Whether it's useful or not remains to be seen.

Q. When the Viterbi decoder receives one signal point what does it do?

MR. TROPP: Objection.

A. What type of system?

Q. Let's say we have a four-dimensional system on the '627 patent.

A. There are many ways to implement procedures. So in my experience it waits for the second sample. And then in each of the states it looks back and calculates the accumulated path metric between the received signal samples of the two intervals and the quantities that it's going to be compared with for each of the state transitions.

Q. What if it doesn't wait, and starts calculating that distance between a signal point

interleaving there the subset identifiers. That's what that interleaver is doing.

Q. Okay. But that interleaving is what enables the invention to achieve the desired result?

MR. TROPP: Objection.

Q. The result being the channel symbols are interleaved as well as the signal points within those channel symbols are interleaved.

MR. TROPP: Same objection.

A. The switching circuit then still maintains, if you look at it -- at the output of the switching circuit you have X0 alpha, X1 alpha, right next to each other, and then he uses 341 to interleave those.

MR. JUISTER: What figure are you looking at?

THE WITNESS: I'm looking at figure 3 of '627.

Q. Okay. And can we agree that the functions performed by the switching circuit as well as the interleaver can be performed in one device using software?

A. When you say -- I mean, "one device"?

- Gitlin -

What do you mean?

Q. I mean one digital signal processor.

A. I mean, that's -- you could probably build a whole receiver on one DSP.

Q. And these functions of signal point interleaver 341 as well as the switching circuit 337 and the 4D QAM encoder can all be written in software?

A. As I said before, it depends upon the clock speed, the capacity of a DSP, relative to the information rates and the number of operations.

Q. But if all those numbers are satisfactory, you could write software that would perform all these functions?

A. Yes. That's generally the way these systems are built today with DSP software.

Q. Okay. Thank you.

On the receiver side, if we move to figure 4, you would agree that the signal point interleaver and the switching is your circuit for 56, they perform --

A. I'm --

Q. I'm sorry, not switching -- the signal point interleaver, 441, and the switching circuit,

431, perform the opposite function of what was done in the trellis -- in the transmitter stage?

(The witness reviews document.)

A. You said 441 and 431?

Q. Yes.

A. They do the deinterleaving.

Q. And similarly, a receiver could implement a digital signal processing chip that performs both of these functions (indicating) via software?

A. Yeah. Depending on the speed, you could write it in software. If the thing is running slow enough you could write this on a general purpose process. Software is software. It only works on the general speed device and the speed at which you're operating.

Q. Okay, thank you.

If you look at figure 3 again, is it possible to design a transmitter to achieve the resulting output differently from what's depicted in figure 3 (indicating)?

A. You mean, starting with the input bits and producing the output?

Q. Yes.

- Gitlin -

A. I wouldn't -- I wouldn't venture an opinion on that right now.

Q. For example, could you put a signal point interleaver, 341, prior to the 4D QAM encoder, and still achieve the same result?

A. Where would you put it?

Q. You would put it, for example, on line 338.

A. Well, the way he has it, 338, what you have there are indices you don't have signal points. So the signal point interleaver -- I mean -- it's a signal point interleaver. You don't have signal points at that point.

Q. I understand that.

But let's assume we're only interested in producing the result on 3 -- on line 342.

Are you with me?

A. No. Oh, okay. 342.

Q. To produce this result, if we were to put an interleaver, 341, on line 338, and the interleaver would interleave the subset identifiers, would the same result be produced?

A. I would say at a minimum you would have to put 341 on line 17 as well as 363. If you want

- Gitlin -

to do interleaver -- on line 317. You want to do interleaving of the uncoded bits as well. Otherwise you would be out of cycle.

Q. So you could put 341 on lines 317 and 338 and still achieve the result on line 342?

A. We're talking here in a functional level?

Q. Yeah, on a functional level.

A. This is a functional diagram. So -- and you -- the terminology, it's no longer a signal point interleaver, it's a signal-something interleaver, because it's not dealing with signal points.

Q. Okay. Let's call it just an interleaver.

So an interleaver would be placed on lines 317 and line 338 to produce the same result as required by the patent on line 342?

A. I have to think about it, if it's exactly the same result. But -- so let me just think about it. I don't want to go any further with this now.

Q. But you stated that it is possible to produce the same result if you were to place an

C E R T I F I C A T E

STATE OF NEW YORK)
: ss.
COUNTY OF NEW YORK)

I, AMY KLEIN, a Shorthand Reporter and Notary Public within and for the State of New York, do hereby certify:

That RICHARD D. GITLIN, the witness whose deposition is hereinbefore set forth, was duly sworn by me and that such deposition is a true record of the testimony given by the witness.

I further certify that I am not related to any of the parties to this action by blood or marriage, and that I am in no way interested in the outcome of this matter.

IN WITNESS WHEREOF, I have hereunto set my hand this 24th day of June, 2008.

Amy Klein

AMY KLEIN

TAB 7

IN THE UNITED STATES DISTRICT COURT
FOR THE DISTRICT OF DELAWARE

In Re: REMBRANDT TECHNOLOGIES, LP PATENT LITIGATION	)	MDL Docket No. 07-md-1848 (GMS)

DECLARATION OF DR. RICHARD D. GITLIN

I, Richard D. Gitlin, declare as follows:

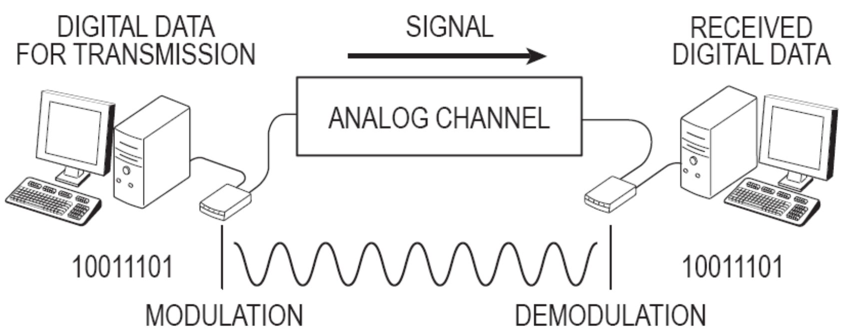
1. The purpose of this declaration is to provide a concise guided tour of the technology in U.S. Pat. No. 5,243,627 — a system and method for transmitting digital data over a communication channel — by discussing three techniques used to reduce a system's error-rate: two-dimensional trellis-coded modulation (2-D TCM), multidimensional (greater than 2-D) TCM, and interleaving. I will also discuss the concept of a *state transition*, which is key to understanding these techniques, and address some of the disputed claim terms from the '627 patent from the perspective of one of ordinary skill in the art. In particular, I explain that a single state transition in a 2-D TCM system produces one expanded bit-group corresponding to one 2-D signal point transmitted in one signaling interval; ***by contrast, a single state transition in a multidimensional TCM system also produces one expanded bit-group, but it corresponds to multiple 2-D signal points transmitted over multiple signaling intervals***.

2. At the end of this month, I will become the Agere-Cerrent Distinguished Professor of Electrical Engineering at the University of South Florida. From 1969 to 2001, I held several positions at AT&T Bell Labs/Lucent Technologies in the field of data communications, including Vice President of R&D and CTO of the Data Networking Systems Group at Lucent and Senior Vice President of Communications Sciences Research at Bell Labs. In those thirty-plus years, I

contributed to and gained experience with a variety of signal processing techniques for information transmission. During my career, I have co-authored the textbook DATA COMMUNICATIONS PRINCIPLES, and have been named as an inventor on over forty patents, and co-authored three prize papers. I have also been honored for my accomplishments by being appointed an IEEE Fellow and an AT&T Bell Labs Fellow, and by being elected a member of the National Academy of Engineering. My curriculum vitae is attached as Exhibit A.

Transmitting Digital Data

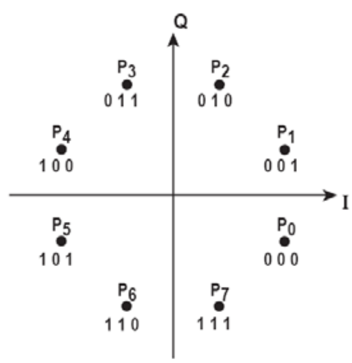
3. Although the most elemental form of digital data are binary digits called *bits*, represented by 1's or 0's, channels that span great distances do not typically carry bits directly. Instead, such channels carry bits indirectly by using a signal known as a *carrier wave*. The transmitted signal is chosen to have characteristics to match those of the analog communication channel, such as its center frequency and bandwidth.



4. Using a process called *modulation*, digital data is transformed into a signal that is appropriate for transmission over a communication channel. As part of this process, a transmitter varies one or more characteristics of a carrier wave (such as its amplitude, frequency, or phase) in response to the information to be communicated over the channel. Typically, carrier waves are modulated once every period of time called a *signaling interval* to convey a group of one or more bits. The process of recovering the digital data from the received signal (i.e., the output of the

channel) is called *demodulation*. A device capable of performing both processes is known as a modem, short for *mo*dulator-*dem*odulator.

5. For modems to communicate successfully, the transmitter will vary the carrier wave in only a limited number of predefined ways, and each variation will uniquely convey a defined number of bits. This type of signaling scheme is graphically represented by a *signal constellation*. For example, shown below is a signaling scheme illustrated as a two-dimensional, circular signal constellation composed of eight *signal points*, P_0–P_7, where each signal point conveys three bits[1] (high-performance, bandwidth-efficient communication systems always convey more than one bit per signal point). Although Fig. 2 of the '627 patent discloses a signal constellation with thirty-two signal points, each corresponding to five bits, the eight-point signaling scheme embodies the same basic principles and reduces the complexity of the examples below.



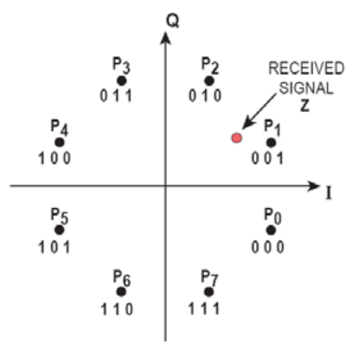
6. Each of the eight signal points on the constellation depicted above represents discrete values of both the *I* and *Q* components of a carrier wave — i.e., a transmitted signal — and conveys a unique group of three bits. The two axes of the signal constellation represent, respectively, the amplitude of the cosine component of the carrier wave (the horizontal or in-phase *I*-axis) and

[1] If each transmitted signal conveys N bits, the constellation requires 2^N signal points, which in our example is 2^3 or eight signal points. In the '627 patent, each transmitted signal conveys five bits, so the constellation requires 2^5 or thirty-two signal points.

the amplitude of the sine component of the carrier wave (the vertical or quadrature *Q*-axis). Accordingly, each signal point may also be referred to by its two coordinate values: (*I*, *Q*)[2]

Channel Noise and Interference

7. Noise, or other impairments in a communication channel, can distort the characteristics of the transmitted, modulated carrier wave. If the noise is large enough, this may cause the receiver to make errors in attempting to recover the transmitted information. For example, assume a transmitter sends the signal corresponding to P_2 and noise causes it to be received as the signal *Z* that has *I* and *Q* values falling between P_2 and P_1 in the signal constellation as illustrated below:



In an uncoded system, a receiver will decide that the transmitter sent the signal point that is closest to the received signal. So in this example, the receiver would decide that the received signal *Z* corresponds to the transmitted signal point P_1, instead of P_2; this would result in bit-errors during reception by outputting the bit sequence 0 <u>0</u> <u>1</u> instead of 0 <u>1</u> <u>0</u>.

8. One means to improve the reliability of an uncoded communication system in the presence of noise and other signal degradations is through the use of error-control codes. These codes introduce extra bits used to improve system performance, e.g., by lowering the system's error-rate. But adding extra bits generally increases the required bandwidth, and the bandwidth is limited in many applications and cannot be easily increased.

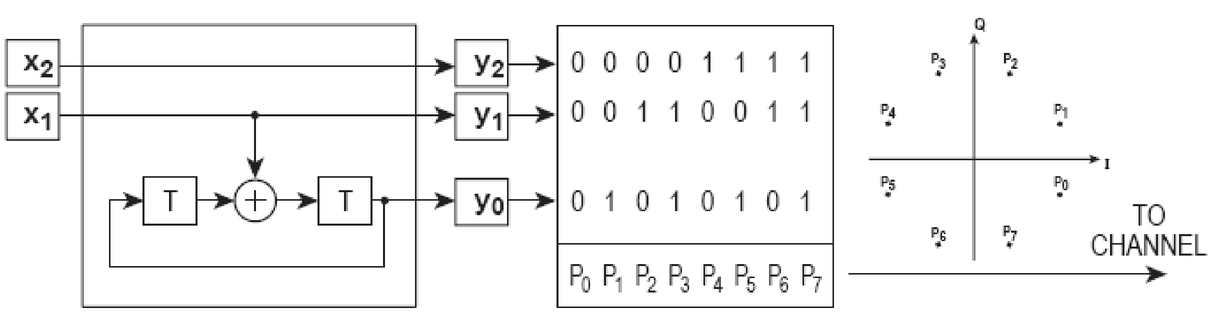
[2] For example, the '627 patent refers to "a transmitted signal point having coordinates (3, -5)" at 5:61-64.

Trellis-Coded Modulation

9. In the 1970s, Gottfried Ungerboeck pioneered a solution to this problem called TCM or *trellis-coded modulation.* TCM combines modulation and coding to improve system performance without increasing the system's bandwidth requirements. As with other error-control techniques, TCM constrains the sequence of transmitted signals, which is the succession, in time, of signals produced by the transmitter. TCM also exploits the constraints on the signaling scheme to increase the distance between allowable signal sequences. The distance between any two signal sequences is a cumulative function of the distance between each sequence's constituent signal points.

10. Increasing distances between allowable sequences lowers the probability that one transmitted sequence will be mistaken for another in the receiver because of channel noise. For example, a receiver knowing that TCM restricts the next signal in the transmitted sequence to P_0, P_4, P_2, or P_6 would not decide that P_1 was transmitted when presented with the received signal Z from the example above since P_1 is not one of the signal points in an allowed sequence.

11. To appreciate how TCM works, consider the relevant components of a TCM system[3] as illustrated below:

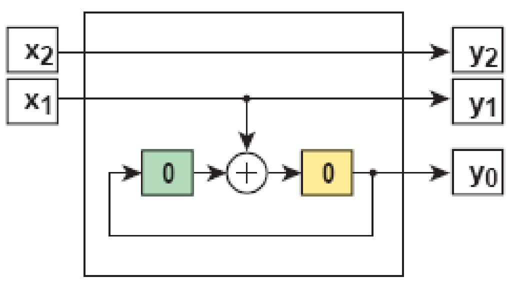


[3] The TCM system used in this section is a simplified version of the four-state trellis-coded eight-phase modulation (*8-PSK*) discussed by Ungerboeck in "Trellis-Coded Modulation with Redundant Signal Sets Part I: Introduction" *IEEE Communications Magazine*, Vol. 25, No. 2, pp. 5-11, February 1987 (attached as Exhibit B) which predates the '627 patent.

The component on the left is an encoder that expands two parallel input bits[4] ($x_2 x_1$) into a three-bit group ($y_2 y_1 y_0$) once every signaling interval as a function of an XOR gate ($\oplus$) and the bit stored in each time-delay element (T); the middle component maps the expanded three-bit groups ($y_2 y_1 y_0$) into one of eight signal points (P_0–P_7) depending on the values of y_2, y_1, and y_0; and the constellation on the right defines each signal point's I and Q coordinates — i.e., the transmitted signals.

State Transitions

12. TCM systems lower the error-rate as described above by using the extra bits produced by time-constrained *state transitions*. In the example encoder, once every signaling interval (T seconds), an extra bit is produced by the XOR gate ($\oplus$), which logically operates on two binary inputs, outputting a 0 when the inputs are the same and a 1 when they differ. As shown below, the bits stored in the time-delay elements (0 0) represent the *state* of the encoder. For example, when both of the stored bits are 0, the encoder's state is S_0:



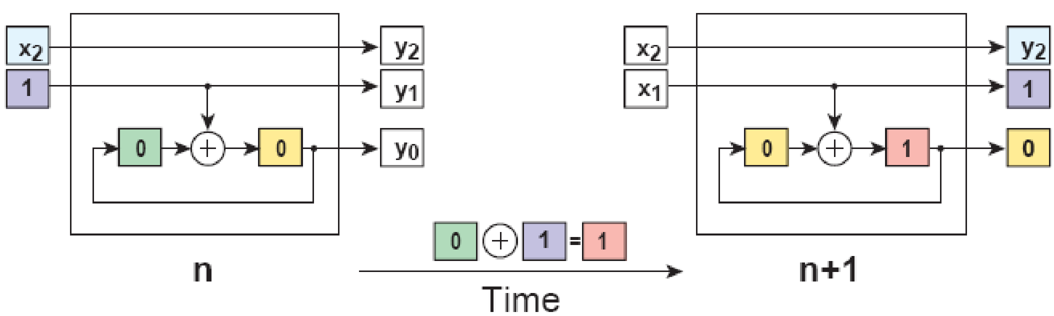
Each time-delay element stores either a 1 or a 0, so the encoder has four possible states: $S_0 = 00$; $S_1 = 01$; $S_2 = 10$; and $S_3 = 11$. Each time the encoder produces an expanded bit-group in response to an input, the bits stored in the time-delay elements are updated. This expansion process results in a new state and is called a *state transition*.

13. As demonstrated below, each state transition depends on the encoder's input as well as its current state. Consequently, the encoder's new state and output are dependent on the encoder's

[4] The serial user input stream (not shown) is converted into two parallel input bit streams.

previous history; because of these dependencies, the allowable values for the new state are constrained. This creates a time-dependency among a sequence of expanded bit-groups from the same encoder. By considering all the allowable sequences of state transitions — and the signal history they represent — a decoder can compare each allowable sequence of state transitions with the sequence of received signals and ultimately determine which signal points were most likely to have been transmitted.

14. At the encoder, the process of choosing signal points can be considered in two parts: some bits identify one of several possible subsets of signal points, and the remaining bits select a particular signal point from within the identified subset. The examples shown below (in color) illustrate how state transitions produce expanded bit-groups that identify subsets of signal points and select particular points from within those subsets. First assume that at time instant *n*, the encoder's state is $S_0 = 00$ and the value of the x_1 input-bit[5] is 1. In response to the input, the encoder undergoes a state transition which produces the output shown on the right side of the figure below — an expanded bit-group.

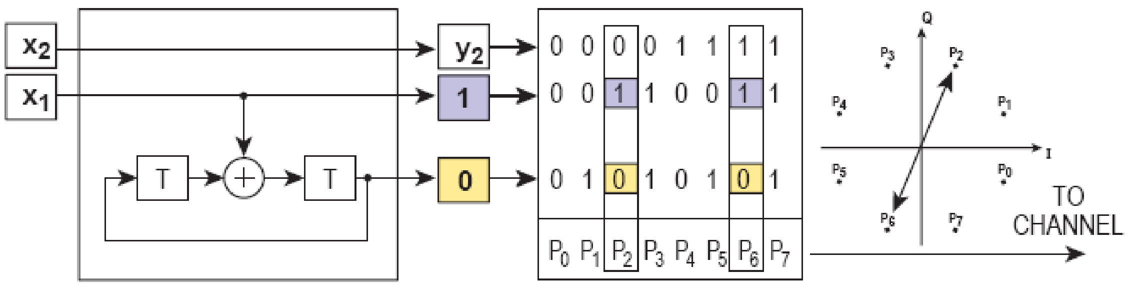


Specifically, the x_2 input-bit ($\boxed{x_2}$) becomes the y_2 output-bit, the x_1 input-bit ($\boxed{1}$) becomes the y_1 output bit, and the bit stored in the right time-delay element ($\boxed{0}$) becomes the y_0 output bit. In addition, the bit stored in the left time-delay element ($\boxed{0}$) is replaced with the bit stored in the right time-delay element ($\boxed{0}$), which is itself replaced by the output of the XOR gate ($\boxed{1}$) based on its two inputs ($\boxed{0}$ and $\boxed{1}$).

---

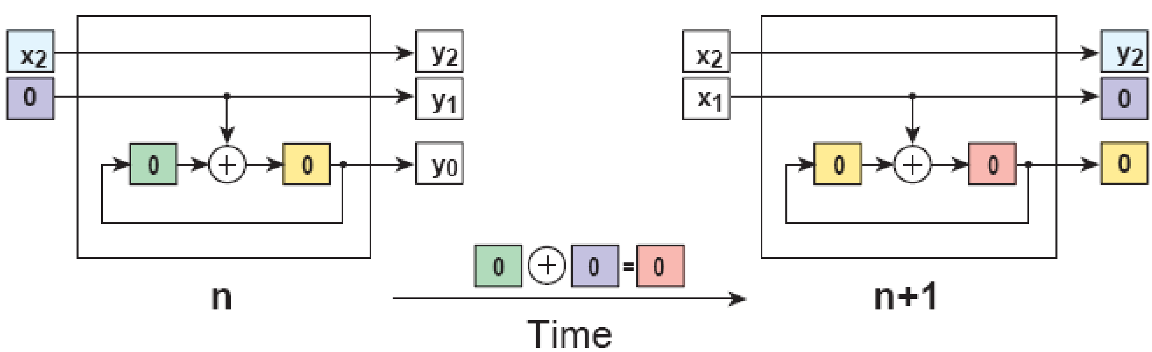
[5] Because the x_2 input-bit is not used to determine the next state of the encoder, it is left unassigned in this example. Its effect on the actual signal point selected is discussed below.

15. Thus, from time instant n to time instant $n+1$, the state transitions from S_0 = 0 0 to S_1 = 0 1 and the encoder produces an expanded bit-group (y2 1 0). As shown below, the y_1 (1) and y_0 (0) bits identify a subset of signal points (P_2 and P_6), and the y_2 bit selects which of those two points will be transmitted.



Note that P_2 and P_6 are separated by the maximum distance possible, lowering the probability that one transmitted sequence of signal points will be mistaken for another in the receiver because of channel noise.

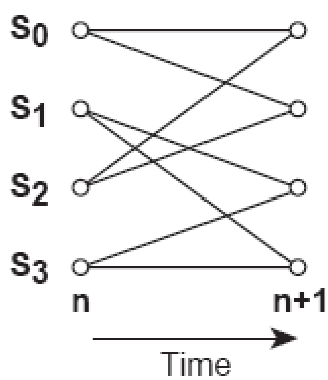
16. If, however, the value of the x_1 input-bit had been 0, the state would have transitioned from S_0 = 0 0 back to S_0 = 0 0 and the encoder would have produced a different expanded bit-group (y2 0 0), which identifies a different subset of signal points[6] (P_0 and P_4) again separated by the maximum distance:



[6] In this example the four possible subsets (00, 01, 10, and 11) are determined solely by the y_1 and y_0 bits. Similarly, the examples in the '627 patent also use two-bit subset identifiers (00, 01, 10, 11) and refer to the resulting four subsets as A, B, C, and D.

Trellis Diagrams

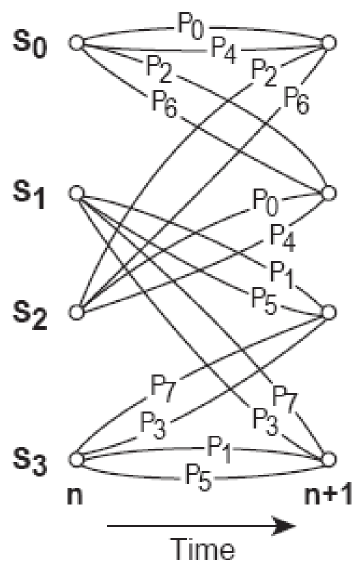
17. The constraint on the number of allowable state transitions produces a limited number of allowable transmitted sequences of signal points, which improves the system's error-rate. The two examples above illustrate the only state transitions from S_0 that are allowed: $S_0 \rightarrow S_1$ or S_0. Transitions from the other initial states are similarly restricted: $S_1 \rightarrow S_2$ or S_3; $S_2 \rightarrow S_0$ or S_1; and $S_3 \rightarrow S_2$ or S_3. Allowable state transitions are graphically represented on a *trellis diagram* (named for its resemblance to a garden trellis). The following trellis diagram illustrates the allowable state transitions for the TCM system discussed here:



The sequence of state transitions produces a path over time ($n+2$, $n+3$, etc…), where each state transition is subject to the same constraints. Each state transition, in addition to producing a new state, produces an expanded bit-group that, in this case, leads to the transmission of one signal point. The TCM receiver will estimate the sequence of transmitted states using the received signal samples and the knowledge of the allowable state transitions. The time dependency between the signal points in the transmitted signal sequence enables the receiver to more accurately estimate the transmitted signal sequences corresponding to the state transitions.

18. Although the x_2 input-bit is not used to determine the next state of the encoder, it does become part of the expanded bit-group as the y_2 bit and is used to select a specific point from the subset of signal points identified by the state transition. In the examples above, x_2 is always equal

to y_2, but more complex TCM systems often use multiple bits to select points from within subsets or perform additional operations on the input bit(s) or both.[7] Here, however, the value of x_2 may only be 1 or 0, so each possible state transition may only result in one of two signal points. The signal points possible with each state transition can be added to the trellis diagram above to illustrate a complete set of restrictions for this TCM system:



19. At the receiver, the decoder analyzes the sequence of received signals, and along with knowledge of the trellis encoding structure, uses the *Viterbi algorithm* to determine the most likely sequence that was sent. Decoders using the Viterbi algorithm analyze the received signals by following multiple paths of state transitions from each state and determining their relative likelihood (or probability) of having been transmitted. In this way, a TCM decoding system estimates the state transition path at the transmitter from one signaling interval to the next for each state. This process of tracking signals through time minimizes the effects of channel noise.

[7] For example, the 2-D TCM system disclosed in the '627 patent sends a group of three bits that are not used to determine the next state of the encoder through a "modulus converter" to produce an "index value" used to select one of eight signal points from one of the subsets A, B, C, or D. ('627 patent at 3:22-36).

Multidimensional TCM

20. The TCM techniques described above are referred to as two-dimensional (2-D), since in each signaling interval both dimensions of the carrier wave (I and Q) are modulated to generate one signal point, for example using the 8-PSK signal constellation described above.

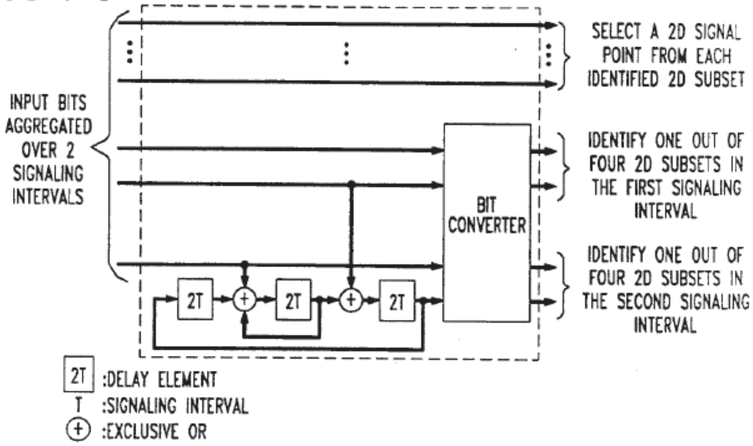
21. In the 1980s, Lee-Fang Wei improved the efficiency of the 2-D TCM described above. As detailed in his paper "Trellis-Coded Modulation with Multidimensional Constellations" (attached as Exhibit C and cited in the '627 patent at 4:48-51), multidimensional TCM schemes with multidimensional (greater than 2-D[8]) signal constellations have a number of potential advantages over the usual 2-D schemes, including further reducing the error-rate relative to 2-D TCM.

22. In 2-D TCM systems, as discussed above, every state transition produces one expanded bit-group that leads to the transmission of one signal point in each signaling interval. In multidimensional TCM systems, as explained in the Wei paper, every state transition still produces one expanded bit-group, but this one expansion now leads to the transmission of multiple signal points over multiple signaling intervals. So, a 4-D TCM system will map the product of one encoder expansion into I and Q components over two signaling intervals (I and Q dimensions over two successive signaling intervals comprise the four dimensions). ***This is a fundamental distinction between 2-D TCM and multidimensional TCM***.

23. For example, Fig. 3 of U.S. Pat. No. 5,214,656 (attached as Exhibit F) which predates the '627 patent, illustrates a 4-D TCM system in which a single state transition (one expansion) produces two signal points: one for transmission in the "first signaling interval" and another for transmission in the "second signaling interval":

[8] Multidimensional signals that consisted of multiple two-dimensional signal points were commonly used in the prior art to the '627 patent. For example, see U.S. Pat. No. 4,641,327 (attached as Exhibit D) at 1:14-26 or U.S. Pat. No. 4,755,998 (attached as Exhibit E) at 3:24-32.

FIG. 3



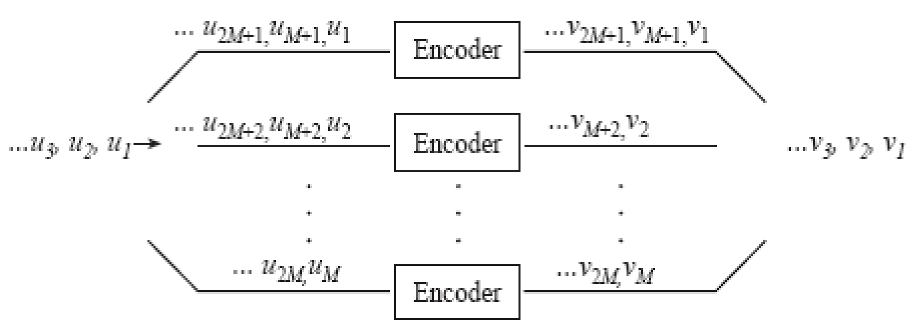
Similarly, Fig. 6 of the Wei paper (Exh. C) cited in the '627 patent also shows a 4-D TCM system in which a single state transition (one expansion) produces two signal points that are transmitted over two signaling intervals. Likewise, although the '627 patent does not disclose the details of the 4-D TCM system used in its examples, it does explain (at 3:65-4:3) that each expansion of the trellis encoder results in the transmission of two signal points. As a result, only one extra bit is added for every two signal points instead of one for every signal point as in 2-D TCM. This improves the transmission efficiency of the system.

24. Multidimensional signal points are interdependent because they are selected together as the result of a single state transition by an encoder. This interdependence is in addition to the time dependence between the expanded bit-groups produced by a sequence of state transitions. In the parlance of the '627 patent, the multiple signal points corresponding to a single state transition of an encoder constitute a trellis-encoded channel symbol. Accordingly, a decoder in a multi-dimensional TCM system needs all of the received signals associated with a single state transition by a corresponding encoder before it begins to process any of them. For example, a decoder in a 4-D TCM receiver will process together the signals that are received over two signaling intervals.

Interleaving

25. While both 2-D and multidimensional TCM systems help correct reception errors caused by noise and interference, it has been observed that their effectiveness decreases when the noise occurs in a burst over several consecutive signaling intervals. As discussed above, decoders using the Viterbi algorithm analyze the received signals by following multiple paths of state transitions from each state and determine their relative likelihood (or probability) of having been transmitted. But if several signaling intervals are impaired by a long burst of noise (i.e., too many steps in the path are obscured), the Viterbi decoder may be unable to correct the errors. This is a well understood effect of noise bursts on coded systems, including TCM systems. Interleaving in time is an established technique for alleviating the effects of such burst noise on a coded system's error rate.

26. If a 2-D TCM system is used, groups of input bits can be divided between multiple encoders and the resulting expanded bit-groups then recombined in an alternating fashion as shown below in an illustration using *n* encoders that is adapted from Fig. 6.10.1. of Robert G. Gallager, INFORMATION THEORY AND RELIABLE COMMUNICATION 287 (John Wiley & Sons 1968) (attached as Exhibit G):[9]

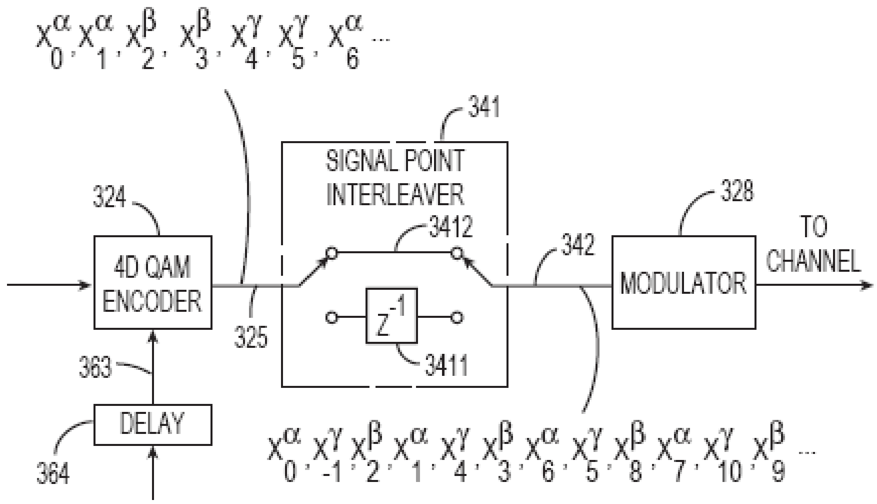


[9] A similar figure appears in the '627 (Fig. 3, elements 331, 319, 337) and in the '625 (Fig. 1, elements 16, 18, 20, 22, 24, 42).

The result is a sequence of transmitted signals in which adjacent signals (those transmitted in consecutive signaling intervals such as v_1 and v_2) are generally unrelated because they were produced using different physical encoders with different inputs (although each encoder might have the same encoding algorithm) and thus producing a different sequence of state transitions. A burst of noise that is longer than *M* signaling intervals would affect multiple transmitted signals from the same encoder. If the received signal points are then divided among a similar arrangement of multiple corresponding decoders, each decoder would process a sequence of received signals that were generated by the same encoder. In this way, any noise effects are spread out over time and each decoder will see isolated effects of the noise burst and each decoder has a much higher probability of correcting the effects of this type of noise.

27. If a multidimensional TCM system is used, however, the product of a single state transition is used to select multiple, interdependent signal points. Thus dividing the groups of input bits between multiple encoders and simply recombining the resulting expanded bit-groups in an alternating fashion would not separate the sets of interdependent signal points, though each set would be separated from the next produced using the same encoder. To separate the interdependent signal points of a single state transition (present only in multidimensional TCM systems) an additional method must be used.

28. For example, the Signal Point Interleaver *341* shown in Fig. 3 of the '627 patent (reproduced below) uses a delay element *3411* to separate the adjacent, interdependent two-dimensional signal points on line *325* (e.g., x_0^α and x_1^α; x_2^β and x_3^β, and x_4^γ and x_5^γ) produced by three separate 4-D encoders α, β, and γ (not shown).



Signal points x_0^α and x_1^α, which are produced by a single state transition of the 4-D encoder α, are adjacent when entering the Signal Point Interleaver 341, but are separated by the signal points x_{-1}^γ and x_2^β upon exiting the interleaver by operation of the delay element *3411*.

29. When x_0^α is input to the Signal Point Interleaver, it is applied to line *3412* and immediately passed through as the output on line *342*. The next input (x_1^α), however, is stored in the delay element 3411, which outputs its previously stored signal point (x_{-1}^γ) on line *342*. Simply repeating this process by holding back every other signal point achieves the desired separation between adjacent, interdependent two-dimensional signal points.

Disputed Claim Terms

30. As explained above, TCM and interleaving are techniques used to overcome burst noise and interference in signaling systems. In the 1980s, William Betts, one of the ’627 patent inventors, patented a multiple-trellis-encoder system for separating channel symbols encoded by any particular encoder from one another on the channel (U.S. Pat. No. 4,677,625 attached as Exhibit H), which is similar to the multiple encoder system in the Gallager book described above. As disclosed in that earlier Betts patent, each channel symbol is separated from the next channel symbol from the same encoder by intervening channel symbols from other trellis encoders in the

system using a round-robin switching circuit. The ’627 patent purports to be an improvement over the ’625 patent specifically for use with *multidimensional* signaling in which each channel symbol comprises multiple, adjacent interdependent signal points. In Betts’ own words, in accordance with the ’627 invention, “it has been realized that the Viterbi decoder performance in a data communication system using 2N-dimensional channel symbols can be further enhanced by an interleaving technique which uses, in combination, a) the aforementioned distributed trellis encoder/Viterbi decoder technique [from the ’625 patent] and b) a signal point interleaving technique which causes the constituent signal points of the channel symbols to be non-adjacent as they traverse the channel.” (’627 patent at 2:5-13.) That is, the improvement claimed in the ’627 patent addresses *multidimensional* trellis encoding and takes the further step of separating the adjacent signal points of each multidimensional channel symbol from one another.

31. I believe Defendants’ proposed construction of “trellis encoded channel symbol … comprised of a plurality of signal points” is correct. Their construction properly reflects the understanding of one of ordinary skill in the art that the ’627 patent and claims are directed to the problem of burst interference in the context of multidimensional signaling. The ’627 patent would be pointless — or at least undifferentiated from the ’625 patent — if there were no inherent relationship between the signal points of a given trellis-encoded channel symbol beyond that which is always present among the stream of signal points processed by the same encoder. Defendants thus properly propose construing the entire phrase “trellis encoded channel symbol…comprised of a plurality of signal points,” because one of ordinary skill in the art would understand this to be the patentees’ way of claiming multidimensional symbols. Moreover, defendants properly construe this language to require “two or more signal points all selected using the same group of parallel input bits as expanded once by a trellis encoder”; i.e., a multidimensional, multiple-signal-point

channel symbol arising from one state transition of a trellis encoder. Rembrandt's proposed construction, in contrast, would not require the multiple signal points of a trellis encoded channel symbol to comprise a multidimensional symbol and so would be inconsistent with the understanding of one of ordinary skill in the art who read the specification and claims of the '627 patent.

32. Similarly, I believe Defendants' proposed construction of "signal point" is correct. Throughout the patent specification, the patentees described multidimensional channel symbols as "2N-dimensional" where N>1. As I have explained, multidimensional channel symbols arise from multiple, interdependent signal points produced by a single state transition of a trellis encoder, which are transmitted over multiple signaling intervals. "2N-dimensional" is a nomenclature commonly used in the art to describe such a multidimensional symbol having N, 2-D signal points.[10] For example, a 4-D symbol has two (N=2) signal points, each with two dimensions. These dimensions represent the I and Q components of the transmitted signal. Defendants' proposed construction of "signal point" as "a point on a 2-dimensional constellation having a pair of coordinates representing two components of a corresponding signal" thus accurately reflects the understanding of one of ordinary skill in the art in accordance with the '627 disclosure and claims. In contrast, Rembrandt's proposed construction of "signal point" simply as a "value that is transmitted by a modulator in one signaling interval" is inadequate because it fails to reflect the patentees' use of the term to mean one of the signal points in a multidimensional symbol.

[10] See, e.g., U.S. Pat. No. 5,214,656 (Exh. F) at 2:59-68.

Conclusion

33. Although there are many possible variations to the techniques discussed above, this declaration illustrated that a fundamental distinction between 2-D TCM and multidimensional TCM is that in 2-D TCM a single state transition of an encoder produces one expanded bit-group corresponding to one 2-D signal point for transmission in one signaling interval while in multidimensional TCM one expanded bit-group will correspond to multiple, interdependent 2-D signal points for transmission over multiple signaling intervals.

I swear under penalty of perjury that the foregoing statements are true and correct to the best of my current knowledge and belief.

Executed this 4th day of June 2008.

Richard D. Gitlin

Dr. Richard D. Gitlin

EXHIBIT A

Richard D. Gitlin

42 Windsor Drive
Little Silver, NJ 07739

Office: 908.385.2802
Home: 732.842.1967
richgitlin@ieee.org

Education

- Eng.Sc. D., Electrical Engineering, Columbia University, 1969. Advisor: Prof. W.R. Bennett. Dissertation: Adaptive Signal Processing.
- M.S., Electrical Engineering, Columbia University, 1965.
- B.E.E., The City College of New York, 1964 [with honors].

.

Employment [detailed accomplishments available on request]

- **2008: Agere-Cerrent Distinguished Professor of Electrical Engineering, University of South Florida.**

- **2005-2008: Chief Technology Officer, Hammerhead Systems (www.hammerheadsystems.com) .** A market leader in providing innovative data networking solutions for wireline, wireless, and cable service providers. Responsible for developing a product line vision, developing core technology, representing product technology and directions with customers, partners, and standards bodies, and management of intellectual property. Personal research contributions in applications aware networking.

- **2004-2005: President, Innovatia Networks**. An early stage wireless networking start-up company focused on exploiting the synergies between 3G/4G and Wireless LANs.

- **2001-2004: Vice President Technology, NEC Laboratories America**
  Responsible for research in Broadband/IP and Mobile Networking, System LSI, Secure Systems, and Quantum IT
  Initiated many systems projects in wireless networks, 4G communications, system LSI, and secure, reliable systems.

1969-2001: Bell Labs, Lucent Technologies

- **1998-2001: Senior Vice President R&D and CTO, Lucent Technologies: Data Networking Systems Group**
  Responsible for applied research, system architecture, standards, and network performance for IP/ATM data networking business unit. Initiatives including Bell Labs high-speed router (Packetstar), Cable Modem Termination System (CMTS), and BLAST commercialization.

- **1995-1998: Senior Research Vice President, Communications Sciences Research [Bell Labs]**
  Responsible for leading and managing a broad range of research programs in broadband (IP/ATM) and computer networking, wireless communications, multimedia systems, and system LSI. Managed ~500 people in 5 research labs, in multiple locations and continents [initiated labs in The Netherlands and the UK --- the first Bell Labs research locations outside the US]. Maintained personal research agenda in wireless and networking and significantly influenced the IS-95B (CDMA) multicode standard. Strong personal contributor to the R&D of WiFi and CDMA systems.

- **1992-1995: Vice President, Communications Systems Research [Bell Labs]**
  Led and managed ~100 research staff lab in communications, broadband networking, and accesss
  Accomplishments: BLAST [MIMO space time coding], Packetstar IP Router/Switch, Atlanta ATM chip set, DoCSIS cable protocol

- **1987-1992: Director, Network Systems Research [Bell Labs]**
  Initiated smart antenna research program, co-inventor of multicode CDMA, 20 Gbps ATM switch, LuckyNet Gigabit testbed, Diversity coding, and Optical Equalization. Strong personal contribution to smart antennas (today referred to as MIMO).

- **1986-1987: Director, Data Communications Research**
  Co-inventor DSL, initiated 56K modem development, helped create Globespan (AT&T DSL spinoff).

- **1969-1986: Director, Supervisor and Member of Staff in Advanced Data Communications**
  Co-inventor of the passband equalizer, and many contributions to QAM systems, coded modulation, echo cancellation, and V.32/V.34 modems.

Academic Positions

- **2001- 2003 Adjunct Professor of Electrical Engineering, Columbia University**
  Completed the supervision of two Ph.D. Students
  Eunsoo Shim: Mobility Management in the Wireless Internet, April 2004
  Hung-yu Wei: Hybrid Wireless Relay Networks, November 2004

- **2000-2001: Visiting Professor of Electrical Engineering, Columbia University**
  - Courses taught: EE 6712x: Communication Theory I ---graduate course
    EE 6713y: Communication Theory II --- graduate course
    EE 6950x: Wireless Networking --- graduate course
  - Research: Wireless Networking and Communications
  - Supervised two Ph.D. students [see above] and several M.S. students.

- **1990-1991: Adjunct Professor of Electrical Engineering, Princeton University:** taught EE526, graduate Communication Theory course

  1973: Adjunct Assistant Professor of Electrical Engineering, Columbia University: taught EE6712, a graduate Communication Theory course

Awards and Honors

- **National Academy of Engineering**, for "contributions to communications systems and networking" (2005)
- **Thomas Alva Edison patent award** for innovation in wireless networking (2005)
- **AT&T Bell Labs Fellow**, for "contributions to data communications" (1987)
- **IEEE Fellow** for "contributions to data communications techniques" (1986)
- **IEEE Communications Society Steven O. Rice Award** for the best original paper published in the ***IEEE Transactions on Communications***: "Analog Diversity Coding to Provide Transparent Self-Healing Communication Networks" [first application of forward error control to realize fault tolerant broadband/optical networks. Co-authors: E. Ayanoglu, I. Bar-David, and Chih-Lin I] (1995)
- **IEEE Communications Society Frederick Ellersick Award** for the best paper published in ***IEEE Communications:*** "Reducing the Effects of Transmission Impairments in Digital Fiber Optic Systems", ***IEEE Communications***, June 1993 [design of gigabit fiber optic equalizer to compensate for polarization mode dispersion]. Co-authors: S. Kasturia and J. Winters (1994).
- ***Bell System Technical Journal Award*** for the best paper in communications science " The Tap-Leakage Algorithm: An Algorithm for the Stable Operation of a Digitally Implemented, Fractionally Spaced Adaptive Equalizer", ***Bell System***

Technical Journal, vol.61, no.8 p.1817-39, Oct. 1982 [invented and analyzed a new class of adaptation algorithms for stabilizing the adjustment of the tap weights in fractionally spaced equalizers]. Co-authors: E. Ho and J. Mazo (1982).

- Honor Societies: Tau Beta Pi, Eta Kappa Nu, and Sigma Xi

Selected Keynote Speeches and Invited Lectures

- MPLS 2006
- Mobicomm 2004
- WCNC 2003
- APOC [Asian Pacific Optical and Wireless Conference] 2002
- Globecomm 1998
- Merlin Memorial Lecture, Technion, 1998

Professional Service

- NAE Nominating committees for the Electronics and Computer Science sections [2006]
- Member, IEEE Communications Society Board of Governors [1988-1991]
- Member, IEEE Communications Society Awards Board [1991-1994]
- President, Communication Theory Group, IEEE Communications Society [1988-1990]
- Chair, Communication Theory Workshop [1992]
- Member, Advisory Board for Computer Science and Engineering [CISE], National Science Foundation [1995-1998]
- Member, Industrial Advisory Board, Department of Electrical Engineering and Computer Science, University of California, Berkeley [1995-1996].
- Advisory/Editorial Board Member
  - Editor, Communication Theory, the *IEEE Transactions on Communications* [1977-1986]
  - *Bell Labs Technical Journal* [founding member in 1996 -2000]
  - *Journal of Communications Networks* [1998-present]
  - *Mobile Networks and Applications* [1996-present]
- Editor of several special issues of communications and networking journals.

Books

1. ***Data Communications Principles***, Gitlin, Hayes, and Weinstein, Plenum Press (1992)

2. ***Wireless Digital Communications and Networks: Systems and Technologies for 3/4G Mobile Communications and the Wireless Internet*** [in preparation ---early stages]

Selected Scientific Papers

1. Coordinated load balancing, handoff/cell-site selection, and scheduling in multi-cell packet data systems, Aimin Sang, Xiaodong Wang, Mohammad Madihian, and Richard D. Gitlin, *Wireless Networks,* June 2006.

2. Incentive Scheduling for Cooperative Relay in WWAN/WLAN Two-Hop-Relay Networks, Hung-yu Wei and Richard D. Gitlin, *WCNC 2005,* March 2005.

3. Dynamic Channel Management in MIMO OFDM Cellular Systems, Ben Lu, Xiaodong Wang, Richard D. Gitlin and Mohammad Madihian, *Wireless Communications and Mobile Computing (J. Wiley Interscience)*, November, 2005.

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6. Coordinated Load Balancing, Handoff/Cellsite Selection, and Scheduling in Multicell Packet Data Systems, A. Sang, M. Madihian, X. Wang, and R.D. Gitlin, *Mobicom 2004*, September 2004.

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Patents: 47 issued United States Patents with 6 applied for and pending.

Short Courses: Short courses at various conferences [Globecomm, ICC, Sigcomm, and OFC] and universities in the areas of

- Wireless Communications and Networks
- Broadband Networks
- Digital Communications
- Adaptive Signal Processing

Selected Accomplishments

Below are selected highlights of my personal ***research*** accomplishments [as opposed to my managerial accomplishments]. Throughout my career, I have maintained a personal research agenda ---even during my years in management. I have tried to list only those contributions that are fundamental and have had significant impact on the research and commercial communities over the years.

Modems and Signal Processing

1. 1973: Co-invention of the **passband equalizer**. This remains the standard equalization structure for Quadrature Amplitude Modulation [QAM]-based systems used in modems, wireless, DSL, cable, etc.
2. 1973: Provided the first fundamental understanding and design guidance for the level of precision needed in ***adaptive*** **digital (finite precision) equalization algorithms** [in contrast to the lower levels of precision needed for non-adaptive equalization or digital filtering].
3. 1982: Provided a fundamental understanding of the **fractionally spaced adaptive equalizer** and invented new adjustment algorithms to ensure proper operation [**BSTJ prize paper**].
4. 1985: Co-invention of **DSL** --- which created an industry [independently, and unknown to us, similar work was also done at Bellcore by J. Lechleider]. Described in US Patent 4924492.

Optical Communications and Networking

1. 1993: Provided fundamental understanding necessary to realize the world's **first adaptive equalizer to compensate for polarization mode dispersion** [**Ellersick prize paper**]. This led to a prototype gigabit per sec equalizer chip. Several research groups and companies are now incorporating these ideas in their next-generation gigabit LANs.
2. 1990: Invented **diversity coding** (the application of forward error/erasure coding across diverse network links ---could be different wavelengths or network paths--- awarded the **Rice prize paper**). This technique is being considered for rapid fault recovery in commercial DWDM systems. [Original invention in 1975 for reliable operation of microwave radio in severe fading].

Wireless Communications and Networking

1. 1994: Provided fundamental understanding of the benefits of **adaptive ("smart) antenna arrays** in increasing the capacity of wireless systems. **Today, 3G systems have standardized this technology.**
2. 1995: Proposed and implemented the first **asymmetric wireless network protocol** (AIRMAIL) to minimize power consumption at the mobile, while not compromising performance.
3. 1995: Invented **multi-code CDMA**-based wireless systems. This technology permits user to efficiently burst at rates approaching the system capacity. **Standardized in 3G wireless**.
4. 2001: Co-inventor of wireless IP-layer fast handoff procedure that became an **IETF RFC**.

EXHIBIT B

Trellis-Coded Modulation with Redundant Signal Sets Part I: Introduction

Gottfried Ungerboeck

Simple four-state trellis-coded modulation (TCM) schemes improve the robustness of digital transmission against additive noise by 3 dB without reducing data rate or requiring more bandwidth than conventional uncoded modulation schemes. With more complex schemes, coding gains up to 6 dB can be achieved. This article describes how TCM works

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Trellis-Coded Modulation (TCM) has evolved over the past decade as a combined coding and modulation technique for digital transmission over band-limited channels. Its main attraction comes from the fact that it allows the achievement of significant coding gains over conventional uncoded multilevel modulation without compromising bandwidth efficiency. The first TCM schemes were proposed in 1976 [1]. Following a more detailed publication [2] in 1982, an explosion of research and actual implementations of TCM took place, to the point where today there is a good understanding of the theory and capabilities of TCM methods. In Part I of this two-part article, an introduction into TCM is given. The reasons for the development of TCM are reviewed, and examples of simple TCM schemes are discussed. Part II [15] provides further insight into code design and performance, and addresses recent advances in TCM.

TCM schemes employ redundant nonbinary modulation in combination with a finite-state encoder which governs the selection of modulation signals to generate coded signal sequences. In the receiver, the noisy signals are decoded by a soft-decision maximum-likelihood sequence decoder. Simple four-state TCM schemes can improve the robustness of digital transmission against additive noise by 3 dB, compared to conventional uncoded modulation. With more complex TCM schemes, the coding gain can reach 6 dB or more. These gains are obtained without bandwidth expansion or reduction of the effective information rate as required by traditional error-correction schemes. Shannon's information theory predicted the existence of coded modulation schemes with these characteristics more than three decades ago. The development of effective TCM techniques and today's signal-processing technology now allow these gains to be obtained in practice.

Signal waveforms representing information sequences are most impervious to noise-induced detection errors if they are very different from each other. Mathematically, this translates into the requirement that signal sequences should have large distance in Euclidean signal space. The essential new concept of TCM that led to the aforementioned gains was to use signal-set expansion to provide redundancy for coding, and to design coding and signal-mapping functions jointly so as to maximize directly the "free distance" (minimum Euclidean distance) between coded signal sequences. This allowed the construction of modulation codes whose free distance significantly exceeded the minimum distance between uncoded modulation signals, at the same information rate, bandwidth, and signal power. The term "trellis" is used because these schemes can be described by a state-transition (trellis) diagram similar to the trellis diagrams of binary convolutional codes. The difference is that in TCM schemes, the trellis branches are labeled with redundant nonbinary modulation signals rather than with binary code symbols.

The basic principles of TCM were published in 1982 [2]. Further descriptions followed in 1984 [3-6], and coincided with a rapid transition of TCM from the research stage to practical use. In 1984, a TCM scheme with a coding gain of 4 dB was adopted by the International Telegraph and Telephone Consultative Commit-

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tee (CCITT) for use in new high-speed voiceband modems [5,7,8]. Prior to TCM, uncoded transmission at 9.6 kbit/s over voiceband channels was often considered as a practical limit for data modems. Since 1984, data modems have appeared on the market which employ TCM along with other improvements in equalization, synchronization, and so forth, to transmit data reliably over voiceband channels at rates of 14.4 kbit/s and higher. Similar advances are being achieved in transmission over other bandwidth-constrained channels. The common use of TCM techniques in such applications, as satellite [9-11], terrestrial microwave, and mobile communications, in order to increase throughput rate or to permit satisfactory operation at lower signal-to-noise ratios, can be safely predicted for the near future.

Classical Error-Correction Coding

In classical digital communication systems, the functions of modulation and error-correction coding are separated. Modulators and demodulators convert an analog waveform channel into a discrete channel, whereas encoders and decoders correct errors that occur on the discrete channel.

In conventional multilevel (amplitude and/or phase) modulation systems, during each modulation interval the modulator maps m binary symbols (bits) into one of $M = 2^m$ possible transmit signals, and the demodulator recovers the m bits by making an independent M-ary nearest-neighbor decision on each signal received. Figure 1 depicts constellations of real- or complex-valued modulation amplitudes, henceforth called signal sets, which are commonly employed for one- or two-dimensional M-ary linear modulation. Two-dimensional carrier modulation requires a bandwidth of 1/T Hz around the carrier frequency to transmit signals at a modulation rate of 1/T signals/sec (baud) without intersymbol interference. Hence, two-dimensional 2^m-ary modulation systems can achieve a spectral efficiency of about m bit/sec/Hz. (The same spectral efficiency is obtained with one-dimensional $2^{m/2}$-ary baseband modulation.)

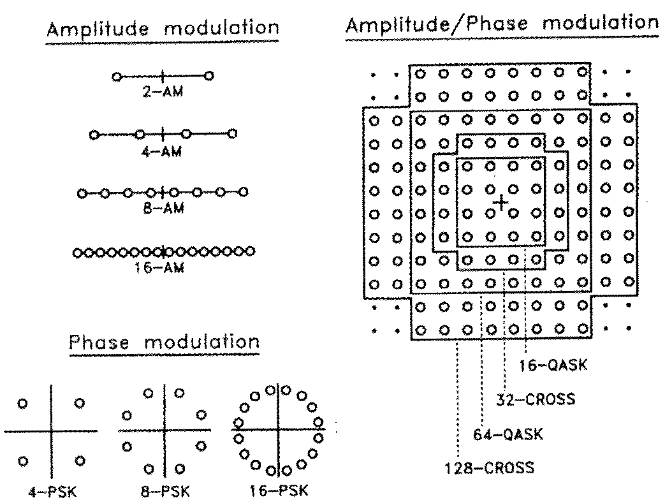

Fig. 1. Signal sets for one-dimensional amplitude modulation, and two-dimensional phase and amplitude/phase modulation.

Conventional encoders and decoders for error correction operate on binary, or more generally Q-ary, code symbols transmitted over a discrete channel. With a code of rate $k/n < 1$, $n - k$ redundant check symbols are appended to every k information symbols. Since the decoder receives only discrete code symbols, Hamming distance (the number of symbols in which two code sequences or blocks differ, regardless of how these symbols differ) is the appropriate measure of distance for decoding and hence for code design. A minimum Hamming distance d^H_{min}, also called "free Hamming distance" in the case of convolutional codes, guarantees that the decoder can correct at least $[(d^H_{min} - 1)/2]$ code-symbol errors. If low signal-to-noise ratios or nonstationary signal disturbance limit the performance of the modulation system, the ability to correct errors can justify the rate loss caused by sending redundant check symbols. Similarly, long delays in error-recovery procedures can be a good reason for trading transmission rate for forward error-correction capability.

Generally, there exist two possibilities to compensate for the rate loss: increasing the modulation rate if the channel permits bandwidth expansion, or enlarging the signal set of the modulation system if the channel is band-limited. The latter necessarily leads to the use of nonbinary modulation ($M > 2$). However, when modulation and error-correction coding are performed in the classical independent manner, disappointing results are obtained.

As an illustration, consider four-phase modulation (4-PSK) without coding, and eight-phase modulation (8-PSK) used with a binary error-correction code of rate 2/3. Both systems transmit two information bits per modulation interval (2 bit/sec/Hz). If the 4-PSK system operates at an error rate of 10^{-5}, at the same signal-to-noise ratio the "raw" error rate at the 8-PSK demodulator exceeds 10^{-2} because of the smaller spacing between the 8-PSK signals. Patterns of at least three bit errors must be corrected to reduce the error rate to that of the uncoded 4-PSK system. A rate-2/3 binary convolutional code with constraint length $\nu = 6$ has the required value of $d^H_{min} = 7$ [12]. For decoding, a fairly complex 64-state binary Viterbi decoder is needed. However, after all this effort, error performance only breaks even with that of uncoded 4-PSK.

Two problems contribute to this unsatisfactory situation.

Soft-Decision Decoding and Motivation for New Code Design

One problem in the coded 8-PSK system just described arises from the independent "hard" signal decisions made prior to decoding which cause an irreversible loss of information in the receiver. The remedy for this problem is soft-decision decoding, which means that the decoder operates directly on unquantized "soft" output samples of the channel. Let the samples be $r_n = a_n + w_n$ (real- or complex-valued, for one- or two-dimensional modulation, respectively), where the a_n are the discrete signals sent by the modulator, and the w_n represent samples of an additive white Gaussian noise process. The decision rule of the optimum sequence decoder is to

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determine, among the set C of all coded signal sequences which a cascaded encoder and modulator can produce, the sequence $\{\hat{a}_n\}$ with minimum squared Euclidean distance (sum of squared errors) from $\{r_n\}$, that is, the sequence $\{\hat{a}_n\}$ which satisfies

$$|r_n - \hat{a}_n|^2 = \min_{\{\hat{a}_n\} \epsilon C} \sum |r_n - a_n|^2.$$

The Viterbi algorithm, originally proposed in 1967 [13] as an "asymptotically optimum" decoding technique for convolutional codes, can be used to determine the coded signal sequence $\{\hat{a}_n\}$ closest to the received unquantized signal sequence $\{r_n\}$ [12,14], provided that the generation of coded signal sequences $\{a_n\} \epsilon C$ follows the rules of a finite-state machine. However, the notion of "error-correction" is then no longer appropriate, since there are no hard-demodulator decisions to be corrected. The decoder determines the most likely coded signal sequence directly from the unquantized channel outputs.

The most probable errors made by the optimum soft-decision decoder occur between signals or signal sequences $\{a_n\}$ and $\{b_n\}$, one transmitted and the other decoded, that are closest together in terms of squared Euclidean distance. The minimum squared such distance is called the squared "free distance:"

$$d^2_{free} = \min_{\{a_n\} \neq \{b_n\}} \sum |a_n - b_n| \; ; \quad \{a_n\}, \{b_n\} \epsilon C.$$

When optimum sequence decisions are made directly in terms of Euclidean distance, a second problem becomes apparent. Mapping of code symbols of a code optimized for Hamming distance into nonbinary modulation signals does not guarantee that a good Euclidean distance structure is obtained. In fact, generally one cannot even find a monotonic relationship between Hamming and Euclidean distances, no matter how code symbols are mapped.

For a long time, this has been the main reason for the lack of good codes for multilevel modulation. Squared Euclidean and Hamming distances are equivalent only in the case of binary modulation or four-phase modulation, which merely corresponds to two orthogonal binary modulations of a carrier. In contrast to coded multilevel systems, binary modulation systems with codes optimized for Hamming distance and soft-decision decoding have been well established since the late 1960s for power-efficient transmission at spectral efficiencies of less than 2 bit/sec/Hz.

The motivation of this author for developing TCM initially came from work on multilevel systems that employ the Viterbi algorithm to improve signal detection in the presence of intersymbol interference. This work provided him with ample evidence of the importance of Euclidean distance between signal sequences. Since improvements over the established technique of adaptive equalization to eliminate intersymbol interference and then making independent signal decisions in most cases did not turn out to be very significant, he turned his attention to using coding to improve performance. In this connection, it was clear to him that codes should be designed for maximum free Euclidean distance rather than Hamming distance, and that the redundancy necessary for coding would have to come from expanding the signal set to avoid bandwidth expansion.

To understand the potential improvements to be expected by this approach, he computed the channel capacity of channels with additive Gaussian noise for the case of discrete multilevel modulation at the channel input and unquantized signal observation at the channel output. The results of these calculations [2] allowed making two observations: firstly, that in principle coding gains of about 7-8 dB over conventional uncoded multilevel modulation should be achievable, and secondly, that most of the achievable coding gain could be obtained by expanding the signal sets used for uncoded modulation only by the factor of two. The author then concentrated his efforts on finding trellis-based signaling schemes that use signal sets of size 2^{m+1} for transmission of m bits per modulation interval. This direction turned out to be succesful and today's TCM schemes still follow this approach.

The next two sections illustrate with two examples how TCM schemes work. Whenever distances are discussed, Euclidean distances are meant.

Four-State Trellis Code for 8-PSK Modulation

The coded 8-PSK scheme described in this section was the first TCM scheme found by the author in 1975 with a significant coding gain over uncoded modulation. It was designed in a heuristic manner, like other simple TCM systems shortly thereafter. Figure 2 depicts signal sets and state-transition (trellis) diagrams for a) uncoded 4-PSK modulation and b) coded 8-PSK modulation with four trellis states. A trivial one-state trellis diagram is shown in Fig. 2a only to illustrate uncoded 4-PSK from the viewpoint of TCM. Every connected path through a trellis in Fig. 2 represents an allowed signal sequence. In

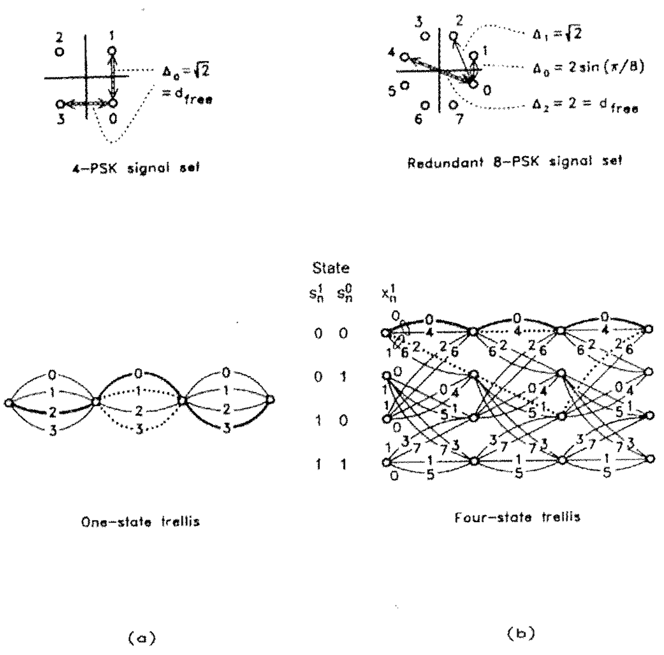

Fig. 2. (a) Uncoded four-phase modulation (4-PSK), (b) Four-state trellis-coded eight-phase modulation (8-PSK).

D0030

both systems, starting from any state, four transitions can occur, as required to encode two information bits per modulation interval (2 bit/sec/Hz). For the following discussion, the specific encoding of information bits into signals is not important.

The four "parallel" transitions in the one-state trellis diagram of Fig. 2a for uncoded 4-PSK do not restrict the sequences of 4-PSK signals that can be transmitted, that is, there is no sequence coding. Hence, the optimum decoder can make independent nearest-signal decisions for each noisy 4-PSK signal received. The smallest distance between the 4-PSK signals is $\sqrt{2}$, denoted as Δ_0. We call it the "free distance" of uncoded 4-PSK modulation to use common terminology with sequence-coded systems. Each 4-PSK signal has two nearest-neighbor signals at this distance.

In the four-state trellis of Fig. 2b for the coded 8-PSK scheme, the transitions occur in pairs of two parallel transitions. (A four-state code with four distinct transitions from each state to all successor states was also considered; however, the trellis as shown with parallel transitions permitted the achievement of a larger free distance.) Fig. 2b shows the numbering of the 8-PSK signals and relevant distances between these signals: $\Delta_0 = 2\sin(\pi/8)$, $\Delta_1 = \sqrt{2}$, and $\Delta_2 = 2$. The 8-PSK signals are assigned to the transitions in the four-state trellis in accordance with the following rules:

a) Parallel transitions are associated with signals with maximum distance Δ_2(8-PSK) = 2 between them, the signals in the subsets (0,4), (1,5), (2,6), or (3,7).
b) Four transitions originating from or merging in one state are labeled with signals with at least distance Δ_1(8-PSK) = $\sqrt{2}$ between them, that is, the signals in the subsets (0,4,2,6) or (1,5,3,7).
c) All 8-PSK signals are used in the trellis diagram with equal frequency.

Any two signal paths in the trellis of Fig. 2(b) that diverge in one state and remerge in another after more than one transition have at least squared distance $\Delta_1^2 + \Delta_0^2 + \Delta_1^2 = \Delta_2^2 + \Delta_0^2$ between them. For example, the paths with signals 0-0-0 and 2-1-2 have this distance. The distance between such paths is greater than the distance between the signals assigned to parallel transitions, Δ_2(8-PSK) = 2, which thus is found as the free distance in the four-state 8-PSK code: $d_{free} = 2$. Expressed in decibels, this amounts to an improvement of 3 dB over the minimum distance $\sqrt{2}$ between the signals of uncoded 4-PSK modulation. For any state transition along any coded 8-PSK sequence transmitted, there exists only one nearest-neighbor signal at free distance, which is the 180° rotated version of the transmitted signal. Hence, the code is invariant to a signal rotation by 180°, but to no other rotations (cf., Part II). Figure 3 illustrates one possible realization of an encoder-modulator for the four-state coded 8-PSK scheme.

Soft-decision decoding is accomplished in two steps: In the first step, called "subset decoding", within each subset of signals assigned to parallel transitions, the signal closest to the received channel output is determined. These signals are stored together with their squared distances from the channel output. In the second step, the Viterbi algorithm is used to find the signal path through the code trellis with the minimum sum of squared distances from the sequence of noisy channel outputs received. Only the signals already chosen by subset decoding are considered.

Tutorial descriptions of the Viterbi algorithm can be found in several textbooks, for example, [12]. The essential points are summarized here as follows: assume that the optimum signal paths from the infinite past to all trellis states at time n are known; the algorithm extends these paths iteratively from the states at time n to the states at time n + 1 by choosing one best path to each new state as a "survivor" and "forgetting" all other paths that cannot be extended as the best paths to the new states; looking backwards in time, the "surviving" paths tend to merge into the same "history path" at some time n − d; with a sufficient decoding delay D (so that the randomly changing value of d is highly likely to be smaller than D), the information associated with a transition on the common history path at time n − D can be selected for output.

Let the received signals be disturbed by uncorrelated Gaussian noise samples with variance σ^2 in each signal dimension. The probability that at any given time the decoder makes a wrong decision among the signals associated with parallel transitions, or starts to make a sequence of wrong decisions along some path diverging for more than one transition from the correct path, is called the error-event probability. At high signal-to-noise ratios, this probability is generally well approximated by

$$Pr(e) \simeq N_{free} \cdot Q[d_{free}/(2\sigma)],$$

where Q(.) represents the Gaussian error integral

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} exp(-y^2/2)dy,$$

and N_{free} denotes the (average) number of nearest-neighbor signal sequences with distance d_{free} that diverge at any state from a transmitted signal sequence, and remerge with it after one or more transitions. The above approximate formula expresses the fact that at high

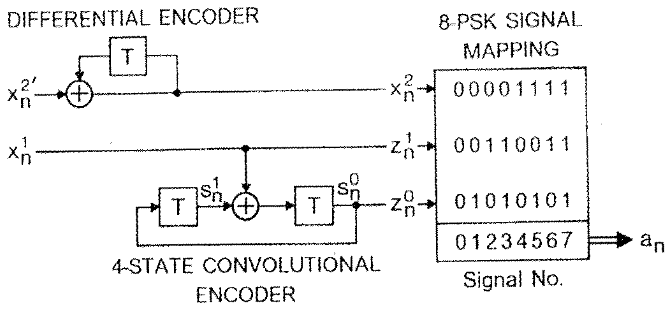

Fig. 3. Illustrates an encoder for the four-state 8-PSK code.

D0031

signal-to-noise ratios the probability of error events associated with a distance larger then d_{free} becomes negligible.

For uncoded 4-PSK, we have $d_{free} = \sqrt{2}$ and $N_{free} = 2$, and for four-state coded 8-PSK we found $d_{free} = 2$ and $N_{free} = 1$. Since in both systems free distance is found between parallel transitions, single signal-decision errors are the dominating error events. In the special case of these simple systems, the numbers of nearest neighbors do not depend on which particular signal sequence is transmitted.

Figure 4 shows the error-event probability of the two systems as a function of signal-to-noise ratio. For uncoded 4-PSK, the error-event probability is extremely well approximated by the last two equations above. For four-state coded 8-PSK, these equations provide a lower bound that is asymptotically achieved at high signal-to-noise ratios. Simulation results are included in Fig. 4 for the coded 8-PSK system to illustrate the effect of error events with distance larger than free distance, whose probability of occurrence is not negligible at low signal-to-noise ratios.

Figure 5 illustrates a noisy four-state coded 8-PSK signal as observed at complex baseband before sampling in the receiver of an experimental 64 kbit/s satellite modem [9]. At a signal-to-noise ratio of $E_s/N_0 = 12.6$ dB (E_s: signal energy, N_0: one-sided spectral noise density), the signal is decoded essentially error-free. At the same signal-to-noise ratio, the error rate with uncoded 4-PSK modulation would be around 10^{-5}.

In TCM schemes with more trellis states and other signal sets, d_{free} is not necessarily found between parallel transitions, and N_{free} will generally be an average number larger than one, as will be shown by the second example.

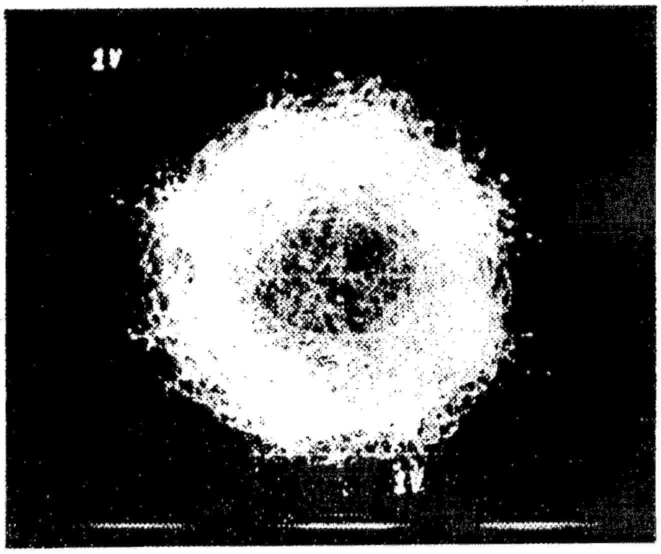

Fig. 5. Noisy four-state coded 8-PSK signal at complex baseband with a signal-to-noise ratio of $E_s/N_0 = 12.6$ dB.

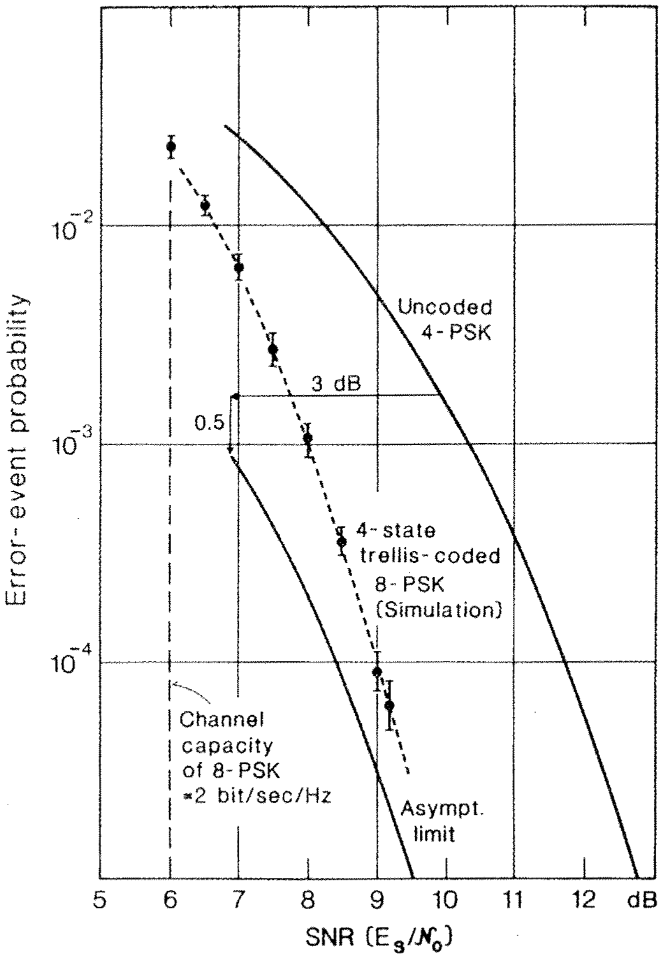

Fig. 4. Error-event probabilty versus signal-to-noise ratio for uncoded 4-PSK and four-state coded 8-PSK.

Eight-State Trellis Code for Amplitude/Phase Modulation

The eight-state trellis code discussed in this section was designed for two-dimensional signal sets whose signals are located on a quadratic grid, also known as a lattice of type "Z_2". The code can be used with all of the signal sets depicted in Fig. 1 for amplitude/phase modulation. To transmit m information bits per modulation interval, a signal set with 2^{m+1} signals is needed. Hence, for m = 3 the 16-QASK signal set is used, for m = 4 the 32-CROSS signal set, and soforth. For any m, a coding gain of approximately 4 dB is achieved over uncoded modulation.

Figure 6 illustrates a "set partitioning" of the 16-QASK and 32-CROSS signal sets into eight subsets. The partitioning of larger signal sets is done in the same way. The signal set chosen is denoted by A0, and its subsets by D0, D1, . . . D7. If the smallest distance among the signals in A0 is Δ_0, then among the signals in the union of the subsets D0,D4,D2,D6 or D1,D5,D3,D7 the minimum distance is $\sqrt{2}\ \Delta_0$, in the union of the subsets D0,D4; D2,D6; D1,D5; or D3,D7 it is $\sqrt{4}\ \Delta_0$, and within the individual subsets it is $\sqrt{8}\ \Delta_0$. (A conceptually similar partitioning of the 8-PSK signal set into smaller signal sets with increasing intra-set distances was implied in the example of coded 8-PSK. The fundamental importance

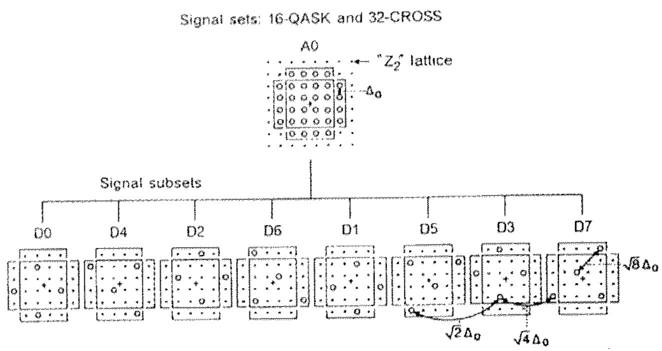

Fig. 6. Set partitioning of the 16-QASK and 32-CROSS signal sets.

of this partitioning for TCM codes will be explained in Part II.)

In the eight-state trellis depicted in Fig. 7, four transitions diverge from and merge into each state. To each transition, one of the subsets D0, . . . D7 is assigned. If A0 contains 2^{m+1} signals, each of its subsets will comprise 2^{m-2} signals. This means that the transitions shown in Fig. 7 in fact represent 2^{m-2} parallel transitions in the same sense as there were two parallel transitions in the coded 8-PSK scheme. Hence, 2^m signals can be sent from each state, as required to encode m bits per modulation interval.

The assignment of signal subsets to transitions satisfies the same three rules as discussed for coded 8-PSK, appropriately adapted to the present situation. The four transitions from or to the same state are always assigned either the subsets D0,D4,D2,D6 or D1,D5,D3,D7. This guarantees a squared signal distance of at least $2\Delta_0^2$ when sequences diverge and when they remerge. If paths remerge after two transitions, the squared signal distance is at least $4\Delta_0^2$ between the diverging transitions, and hence the total squared distance between such paths will be at least $6\Delta_0^2$. If paths remerge after three or more transitions, at least one intermediate transition contributes an additional squared signal distance Δ_0^2, so the squared distance between sequences is at least $\sqrt{5}\ \Delta_0$.

Hence, the free distance of this code is $\sqrt{5}\ \Delta_0$. This is smaller than the minimum signal distance within in the subsets D0, . . . D7, which is $\sqrt{8}\ \Delta_0$. For one particular code sequence D0-D0-D3-D6, Fig. 6 illustrates four error paths at distance $\sqrt{5}\ \Delta_0$ from that code sequence; all starting at the same state and remerging after three or four transitions. It can be shown that for any code

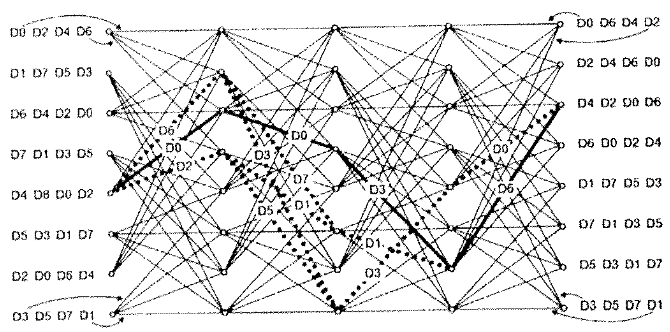

Fig. 7. Eight-state trellis code for amplitude/phase modulation with "Z_2"-type signal sets; $d_{free} = \sqrt{5}\ \Delta_0$.

sequence and from any state along this sequence, there are four such paths, two of length three and two of length four. The most likely error events will correspond to these error paths, and will result in bursts of decision errors of length three or four.

The coding gains asymptotically achieved at high signal-to-noise ratios are calculated in decibels by

$$G_{c/u} = 10 \log_{10} [(d_{free,c}^2/d_{free,u}^2)/E_{s,c}/E_{s,u})],$$

where $d_{free,c}^2$ and $d_{free,u}^2$ are the squared free distances, and $E_{s,c}$ and $E_{s,u}$ denote the average signal energies of the coded and uncoded schemes, respectively. When the signal sets have the same minimum signal spacing Δ_0, $d_{free,c}^2/d_{free,u}^2 = 5$, and $E_{s,c}/E_{s,u} \simeq 2$ for all relevant values of m. Hence, the coding gain is $10 \log_{10}(5/2) \simeq 4$ dB.

The number of nearest neighbors depends on the sequence of signals transmitted, that is N_{free} represents an average number. This is easy to see for uncoded modulation, where signals in the center of a signal set have more nearest neighbors than the outer ones. For uncoded 16-QASK, N_{free} equals 3. For eight-state coded 16-QASK, N_{free} is around 3.75. In the limit of large "Z_2"-type signal sets, these values increase toward 4 and 16 for uncoded and eight-state coded systems, respectively.

Trellis Codes of Higher Complexity

Heuristic code design and checking of code properties by hand, as was done during the early phases of the development of TCM schemes, becomes infeasible for codes with many trellis states. Optimum codes must then be found by computer search, using knowledge of the general structure of TCM codes and an efficient method to determine free distance. The search technique should also include rules to reject codes with improper or equivalent distance properties without having to evaluate free distance.

In Part II, the principles of TCM code design are outlined, and tables of optimum TCM codes given for one-, two-, and higher-dimensional signal sets. TCM encoder/modulators are shown to exhibit the following general structure: (a) of the m bits to be transmitted per encoder/modulator operation, $\tilde{m} \leq m$ bits are expanded into $\tilde{m} + 1$ coded bits by a binary rate-$\tilde{m}/(\tilde{m}+1)$ convolutional encoder; (b) the $\tilde{m} + 1$ coded bits select one of $2^{\tilde{m}+1}$ subsets of a redundant 2^{m+1}-ary signal set; (c) the remaining $m-\tilde{m}$ bits determine one of $2^{m-\tilde{m}}$ signals within the selected subset.

New Ground Covered by Trellis-Coded Modulation

TCM schemes achieve significant coding gains at values of spectral efficiency for which efficient coded-modulation schemes were not previously known, that is, above and including 2 bit/sec/Hz. Figure 8 shows the free distances obtained by binary convolutional coding with 4-PSK modulation for spectral efficiencies smaller than 2 bit/sec/Hz, and by TCM schemes with two-dimensional signal sets for spectral efficiencies equal to or larger than 2 bit/sec/Hz. The free distances of uncoded modulation at the respective spectral effi-

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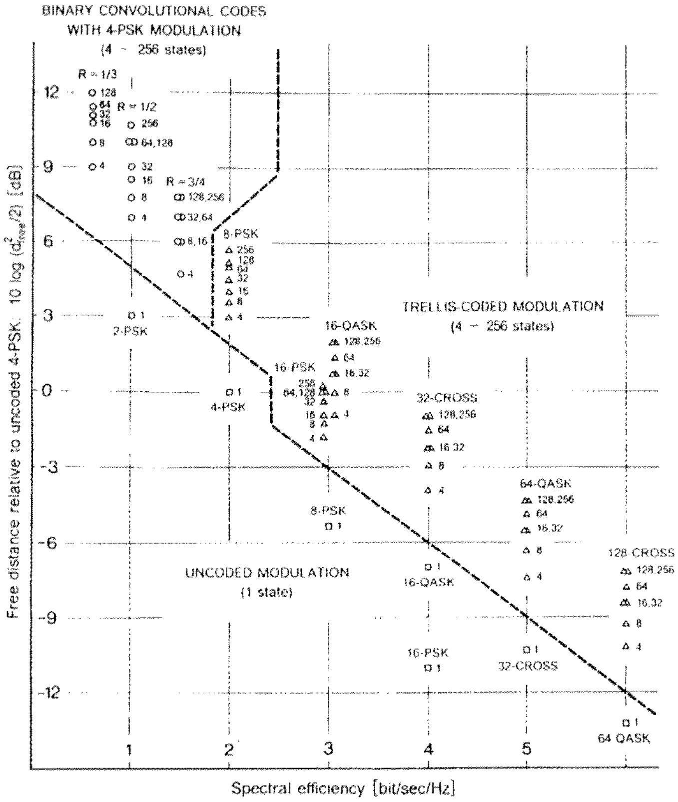

Fig. 8. Free distance of binary convolutional codes with 4-PSK modulation, and TCM with a variety of two-dimensional modulation schemes, for spectral efficiencies from 2/3 to 6 bit/sec/Hz.

ciencies are also depicted. The average signal energy of all signal sets is normalized to unity. Free distances are expressed in decibels relative to the value $d^2_{free} = 2$ of uncoded 4-PSK modulation. The binary convolutional codes of rates 1/3, 1/2, and 3/4 with optimum Hamming distances are taken from textbooks, such as, [12]. The TCM codes and their properties are found in the code tables presented in Part II (largely reproduced from [2]).

All coded systems achieve significant distance gains with as few as 4, 8, and 16 code states. Roughly speaking, it is possible to gain 3 dB with 4 states, 4 dB with 8 states, nearly 5 dB with 16 states, and up to 6 dB with 128 or more states. The gains obtained with two-state codes usually are very modest. With higher numbers of states, the incremental gains become smaller. Doubling the number of states does not always yield a code with larger free distance. Generally, limited distance growth and increasing numbers of nearest neighbors, and neighbors with next-larger distances, are the two mechanisms that prevent real coding gains from exceeding the ultimate limit set by channel capacity. This limit can be characterized by the signal-to-noise ratio at which the channel capacity of a modulation system with a 2^{m+1}-ary signal set equals m bit/sec/Hz [2] (see also Fig. 4).

Conclusion

Trellis-coded modulation was invented as a method to improve the noise immunity of digital transmission systems without bandwidth expansion or reduction of data rate. TCM extended the principles of convolutional coding to nonbinary modulation with signal sets of arbitrary size. It allows the achievement of coding gains of 3–6 dB at spectral efficiencies equal to or larger than 2 bit/sec/Hz. These are the values at which one wants to operate on many band-limited channels. Thus, a gap in the theory and practice of channel coding has been closed.

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EXHIBIT C

IEEE TRANSACTIONS ON INFORMATION THEORY, VOL. IT-33, NO. 4, JULY 1987

Trellis-Coded Modulation with Multidimensional Constellations

LEE-FANG WEI, MEMBER, IEEE

Abstract—**Trellis-coded modulation schemes using four-, eight-, or 16-dimensional constellations have a number of potential advantages over the usual two-dimensional schemes: a smaller constituent two-dimensional constellation, easier tolerance to phase ambiguities, and a better trade-off between complexity and coding gain. A number of such schemes are presented and evaluated. Starting with a variety of multidimensional lattices, we show how to select multidimensional constellations, how to partition them into subsets, how to construct trellis codes using those subsets, and how to map bits to constellation points. Simplifications of the Viterbi decoding algorithm are presented. We conclude that there are multidimensional trellis-coded modulation schemes that perform better for the same complexity than do two-dimensional schemes.**

I. Introduction

TRELLIS-CODED modulation schemes using two-dimensional (2D) constellations have been shown to improve the error performance of synchronous data links without sacrificing data rate or requiring more bandwidth [1]–[3]. In these schemes, to send Q information bits in each signaling interval, a 2D constellation of 2^{Q+1} points is used. The constellation is partitioned into 2^{m+1} subsets with enlarged intrasubset minimum Euclidean distance. Of the Q bits that arrive in each signaling interval, m enter a rate-$m/m+1$ trellis encoder, and the resulting $m+1$ coded bits specify which subset is to be used. The remaining information bits specify which point from the selected subset is to be transmitted.

An eight-state nonlinear trellis code with 4-dB coding gain has now been adopted in the international CCITT standards V.32 for 9.6-kbit/s transmission over the switched telephone network and V.33 for 14.4-kbit/s transmission over private lines [2], [4], [5]. The 2D constellations used in those two standards are the 32-point cross constellation (32-CR) and the 128-point cross constellation (128-CR), respectively. The use of a nonlinear trellis code allows the scheme to be immune to the 90° phase ambiguities of those constellations [2], [6].

To improve the performance of the eight-state trellis code further, more states may be used. However, the returns are diminishing. The coding gain increases more slowly and the error coefficient (the multiplicity of minimum-Euclidean-distance error events) of the code starts to dominate performance.

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The author was with the Codex Corporation, Mansfield, MA 02048. He is now with AT&T Bell Laboratories, Crawford Hill Laboratory, Holmdel, NJ 07733, USA.
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An inherent cost of these coded schemes is that the size of the 2D constellation is doubled over uncoded schemes. This is due to the fact that a redundant bit is added every signaling interval. Without that cost, the coding gain of those coded schemes would be 3 dB greater. Using a multidimensional (> 2) constellation with a trellis code of rate $m/m+1$ can reduce that cost because fewer redundant bits are added for each 2D signaling interval [3]. For example, that cost is reduced to about 1.5 or 0.75 dB if four-dimensional (4D) or eight-dimensional (8D) constellations are used, respectively. Additional coding gain may also be derived from the multidimensional constellation itself [3], [7]–[12]. These observations motivated the investigation of trellis-coded modulation using multidimensional constellations.

Trellis-coded modulation schemes using 4D constellations have been reported in several papers [3], [13]–[15]. In both [3] and [15], the 4D constellation is taken from the 4D rectangular lattice. The 4D constellation is partitioned into 16 4D subsets with four times larger intrasubset minimum squared Euclidean distance (MSED). In [3], the partitioning of the 4D constellation is based on the partitioning of each constituent 2D constellation into four 2D subsets; each 4D subset is formed by concatenating a pair of 2D subsets. In [15], the partitioning of the 4D constellation is done algebraically without referring to the partitioning of the constituent 2D constellations. However, the results of the two partitionings are the same. Three of the $2Q$ information bits arriving in each block of two signaling intervals enter a rate-3/4 eight-state trellis encoder with a minimum free Hamming distance of four. The resulting four coded bits specify which 4D subset is to be used. The remaining information bits specify which point from the selected 4D subset is to be transmitted. The 4D constellation therefore has 2^{2Q+1} points. The mapping of coded bits to 4D subsets is such that the Hamming distance between any two different groups of four coded bits is proportional to the MSED between the two corresponding 4D subsets. The coding gain therefore is approximately 4.5 dB, which is a gain of 6 dB from the trellis code if the 4D constellation were not expanded from 2^{2Q} to 2^{2Q+1} points, less 1.5 dB due to that expansion.

Both references, however, did not address other issues such as error coefficient, phase ambiguities of constellation, and complexity. It was not clear whether those eight-state 4D trellis-coded modulation schemes performed better for the same complexity than did two-dimensional

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schemes. It was also not clear how to construct other multidimensional trellis-coded modulation schemes.

In this paper, a novel geometrical approach to partitioning multidimensional lattices into sublattices with enlarged intrasublattice MSED is described in Section II. The approach simplifies both the construction of multidimensional trellis-coded modulation schemes and the corresponding maximum-likelihood decoding. It therefore opens the door to extensive studies of trellis-coded modulation using various multidimensional lattices. The lattices considered are the 4D, 8D, and 16D rectangular lattices, the densest 4D lattice D_4, the densest 8D lattice E_8, and an 8D lattice which is the union of E_8 and a rotated version of E_8. This latter 8D lattice has not been used before and will be referred to as DE_8 (D stands for double) in this paper. The partitioning of these lattices is based on the partitioning of their constituent 2D rectangular lattices. Further, the partitioning of a multidimensional lattice is done in an iterative manner. That is, the partitioning of a $2N$-dimensional lattice is based on the partitioning of the constituent N-dimensional lattices, which is in turn based on the partitioning of the constituent $N/2$-dimensional lattices. To make the resulting trellis-coded modulation schemes transparent to the phase ambiguities of a multidimensional lattice, the partitioning of the lattice into sublattices is also done such that each sublattice is rotationally invariant to as many phase ambiguities as possible.

In Section III, we show how to construct a finite multidimensional constellation from an infinite multidimensional lattice. The construction of the multidimensional constellation makes it possible to convert a complicated multidimensional constellation mapping into multiple simple constituent 2D constellation mappings. The size of the constituent 2D constellations and the peak-to-average power ratio (of the multidimensional constellation) are also reduced as a result of this construction process. Both the small size and small peak-to-average power ratio are desirable in a communication system where impairments other than additive Gaussian noise, such as linear or nonlinear distortion or phase jitter, are also present, of which voiceband data transmission is an example. With all of these desirable characteristics, the construction process leads the way to practical applications of multidimensional trellis-coded modulation. The partitioning of the multidimensional lattice underlies the partitioning of the multidimensional constellation.

Section IV is the main section of this paper. A number of trellis codes using various partitionings of various multidimensional constellations obtained in the previous two sections are presented. General principles for constructing those codes are discussed. The codes are evaluated in terms of their coding gain, error coefficient, transparency to phase ambiguities, size of constituent 2D constellations, peak-to-average power ratio, and complexity.

A simplified maximum-likelihood decoding algorithm is described in Section V. In that algorithm, the point in each multidimensional subset closest to a received multidimensional point is also found in an iterative manner, as in the partitioning of multidimensional lattices described in Section II. Section VI compares various trellis-coded modulation schemes using multidimensional or 2D constellations and concludes the paper.

II. Partitioning of Multidimensional Lattices

In this section, we show how a multidimensional lattice may be geometrically partitioned into sublattices with enlarged intrasublattice MSED, based iteratively on a partitioning of the constituent 2D lattices. We first give an example, showing how a 4D rectangular lattice with MSED d_0^2 may be partitioned into eight sublattices with MSED $4d_0^2$. We then give general principles for partitioning multidimensional lattices. Those principles are applied to partition the 4D, 8D, and 16D rectangular lattices, the densest 4D lattice D_4, the densest 8D lattice E_8, and a previously unused 8D lattice DE_8. These partitionings will be used in Section IV to construct trellis-coded modulation schemes. The relationships between the sublattices and known lattices such as D_4 and E_8 will also be noted and exploited.

To partition the 4D rectangular lattice with MSED d_0^2 into eight 4D sublattices with MSED $4d_0^2$, each constituent 2D rectangular lattice with MSED d_0^2 is first partitioned into two 2D families $A \cup B$ and $C \cup D$ with MSED $2d_0^2$, which are further partitioned into four 2D sublattices A, B, C, and D with MSED $4d_0^2$, as shown in Fig. 1 (note that the infinite 2D rectangular lattices underlying the finite constellations of Figs. 1–3 are meant when those constellations are referred to in this section). Each 2D sublattice comprises those points designated by the same lower case letter.

Sixteen 4D types may then be defined, each corresponding to a concatenation of a pair of 2D sublattices, and denoted as (A, A), $(A, B), \cdots,$ and (D, D). The MSED of each 4D type is $4d_0^2$, the same as that of the constituent 2D sublattices. The 16 4D types may be grouped into eight 4D sublattices, denoted as 0, $1, \cdots,$ and 7, as shown in Table I. The grouping, while yielding only half as many 4D sublattices as 4D types, is done in a way which maintains the MSED of each 4D sublattice at $4d_0^2$. The advantages of grouping are that with fewer 4D sublattices, the construction of trellis codes using those sublattices is simplified, and the complexity of the corresponding maximum-likelihood decoding is reduced. Furthermore, note that the 4D sublattices of Table I are invariant under 180° rotation, while the 4D types are not. Therefore, the construction of rotationally invariant trellis codes using those sublattices does not need to consider 180° rotation and is thus simplified. The advantages of grouping will be even greater in the case of eight- or higher-dimensional lattices.

The MSED of the 4D sublattices is verified to be $4d_0^2$ as follows. The two first constituent 2D sublattices associated with the two 4D types in each 4D sublattice span a 2D family $A \cup B$ or $C \cup D$, and likewise for the two second constituent 2D sublattices associated with each 4D sublattice. Because the MSED of each 2D family is $2d_0^2$, the MSED of each 4D sublattice is $4d_0^2$.

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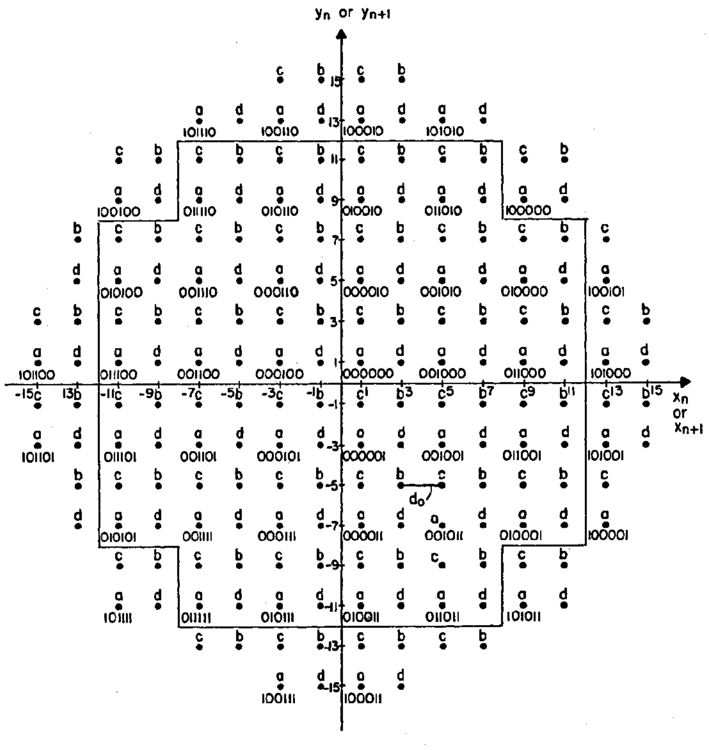


Fig. 1. 192-point 2D constellation partitioned into four subsets.

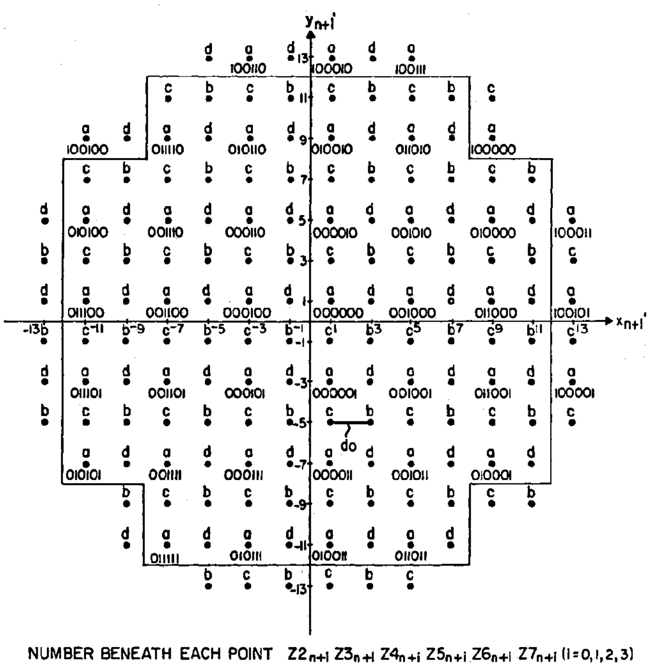
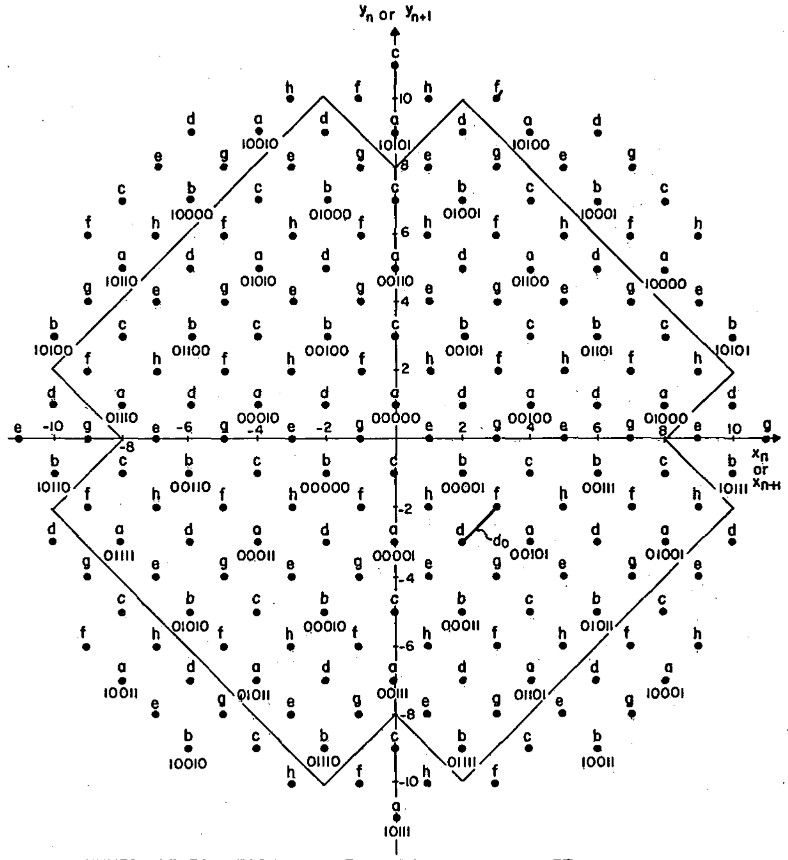


Fig. 2. 160-point 2D constellation partitioned into four subsets.

The 4D sublattices are further grouped into two 4D families $\cup_{i=0}^{3} i$ and $\cup_{i=4}^{7} i$ with MSED $2d_0^2$. The two 4D families may be obtained from the two 2D families in the same way that we obtain 4D sublattices from 2D sublattices.

Before we proceed to describe the general partition principles, we clarify our terminology. A lattice is partitioned into families, subfamilies, and sublattices with (strictly) increasing MSED. Only the bottom level of a partitioning is referred to as sublattice. This level will be assigned to the state transition, or equivalently, specified by the output bits of a trellis code (see Section IV). The intermediate levels, if any, are named first as family, and then as subfamily. If there are more than two intermediate levels, then all the additional levels are referred to as subfamily. Each of these levels of a partitioning of a lattice will play a different role in our construction of trellis codes to be described in Section IV.

Associated with each partitioning of a $2N$-dimensional lattice are partitionings of its constituent N-dimensional and two-dimensional lattices into families, subfamilies, and sublattices with increasing MSED. The $2N$-, N-, and two-dimensional sublattices all have the same MSED. A $2N$-dimensional sublattice may be further partitioned into types and subtypes with the same MSED. Each $2N$-dimensional type is a concatenation of a pair of N-dimensional sublattices. Further, each $2N$-dimensional subtype is a concatenation of N two-dimensional sublattices. The $2N$-dimensional type plays an important role in the partitioning of the $2N$-dimensional lattice into sublattices, and in the corresponding maximum-likelihood decoding to be described in Section V. The $2N$-dimensional subtype plays a role in the $2N$-dimensional constellation mapping to be described in Section IV.



NUMBER BENEATH EACH POINT: $Z3_{n+i}$ $Z4_{n+i}$ $Z5_{n+i}$ $Z6_{n+i}$ $Z7_{n+i}$ ($i = 0, 1$)

Fig. 3. 192-point 2D constellation partitioned into eight subsets.

TABLE I
EIGHT-SUBLATTICE PARTITIONING OF 4D RECTANGULAR LATTICE

4D Sublattice (Subset)	$Y0_n$	$I1_n$	$I2'_n$	$I3'_n$	4D Types	$Z0_n$	$Z1_n$	$Z0_{n+1}$	$Z1_{n+1}$
0	0	0	0	0	(A, A)	0	0	0	0
	0	0	0	1	(B, B)	0	1	0	1
1	0	0	1	0	(C, C)	1	0	1	0
	0	0	1	1	(D, D)	1	1	1	1
2	0	1	0	0	(A, B)	0	0	0	1
	0	1	0	1	(B, A)	0	1	0	0
3	0	1	1	0	(C, D)	1	0	1	1
	0	1	1	1	(D, C)	1	1	1	0
4	1	0	0	0	(A, C)	0	0	1	0
	1	0	0	1	(B, D)	0	1	1	1
5	1	0	1	0	(C, B)	1	0	0	1
	1	0	1	1	(D, A)	1	1	0	0
6	1	1	0	0	(A, D)	0	0	1	1
	1	1	0	1	(B, C)	0	1	1	0
7	1	1	1	0	(C, A)	1	0	0	0
	1	1	1	1	(D, B)	1	1	0	1

In general, the partitioning of a $2N$-dimensional lattice into families, subfamilies, and sublattices with increasing MSED may be done as follows. Suppose that the desired MSED of each $2N$-dimensional sublattice is DIST. The first step is to partition its constituent N-dimensional lattices into families, subfamilies, and sublattices with increasing MSED. Each finer partitioning of the N-dimensional lattice increases the MSED by a factor of two, with the MSED of each N-dimensional sublattice also equal to DIST. The second step is to form $2N$-dimensional types, each type corresponding to a concatenation of a pair of N-dimensional sublattices. The MSED of each $2N$-dimensional type is thus also DIST. Those $2N$-dimensional types are then grouped into $2N$-dimensional sublattices with the same MSED DIST, based on the N-dimensional subfamilies. To reduce the number of $2N$-dimensional sublattices,

we should group as many $2N$-dimensional types into a $2N$-dimensional sublattice as possible. Let us say that there are M N-dimensional sublattices in each N-dimensional subfamily. Each $2N$-dimensional sublattice then comprises M $2N$-dimensional types. The M first constituent N-dimensional sublattices of the M $2N$-dimensional types in each $2N$-dimensional sublattice span an N-dimensional subfamily, and likewise for the M second constituent N-dimensional sublattices associated with each $2N$-dimensional sublattice.

Those $2N$-dimensional sublattices are further grouped into $2N$-dimensional subfamilies and families with decreasing MSED. Each grouping reduces the MSED by a factor of two. The $2N$-dimensional subfamilies or families with a certain MSED may be obtained from the N-dimensional subfamilies or families with the same MSED by following the same principles used earlier to obtain $2N$-dimensional sublattices.

To simplify the construction of rotationally invariant trellis codes using those sublattices, the grouping of $2N$-dimensional types into sublattices should be done in such a way that each sublattice is invariant under as many rotations as possible, each rotation corresponding to a phase ambiguity of the lattice. If it is not possible to make sublattices invariant to all rotations, then each rotation should at least take a sublattice into another sublattice.

The principles just described may be used iteratively to partition a multidimensional lattice based on a partitioning of the constituent 2D lattices. For example, using those principles, the 8D rectangular lattice with MSED d_0^2 may be partitioned into 16 8D sublattices with MSED $4d_0^2$, based iteratively on the partitioning of each constituent 2D rectangular lattice into four 2D sublattices A, B, C, and D as shown in Figs. 1 and 2.

The partitioning of the 8D rectangular lattice is described in the following. The first and second constituent 2D rectangular lattices form a constituent 4D rectangular lattice. As in the example given earlier, this 4D rectangular

TABLE II
16-SUBLATTICE PARTITIONING OF 8D RECTANGULAR LATTICE

8D Sublattice (Subset)	$Y0_n$	$I1_n$	$I2_n$	$I3_n$	8D Types
0	0	0	0	0	(0,0), (1,1), (2,2), (3,3)
1	0	0	0	1	(0,1), (1,0), (2,3), (3,2)
2	0	0	1	0	(0,2), (1,3), (2,0), (3,1)
3	0	0	1	1	(0,3), (1,2), (2,1), (3,0)
4	0	1	0	0	(4,4), (5,5), (6,6), (7,7)
5	0	1	0	1	(4,5), (5,4), (6,7), (7,6)
6	0	1	1	0	(4,6), (5,7), (6,4), (7,5)
7	0	1	1	1	(4,7), (5,6), (6,5), (7,4)
8	1	0	0	0	(0,4), (1,5), (2,6), (3,7)
9	1	0	0	1	(0,5), (1,4), (2,7), (3,6)
10	1	0	1	0	(0,6), (1,7), (2,4), (3,5)
11	1	0	1	1	(0,7), (1,6), (2,5), (3,4)
12	1	1	0	0	(4,0), (5,1), (6,2), (7,3)
13	1	1	0	1	(4,1), (5,0), (6,3), (7,2)
14	1	1	1	0	(4,2), (5,3), (6,0), (7,1)
15	1	1	1	1	(4,3), (5,2), (6,1), (7,0)

TABLE III
32-SUBLATTICE PARTITIONING OF 4D RECTANGULAR LATTICE

4D Family	4D Subfamily	4D Sublattice (Subset)	$Y0_n$	$I1_n$	$I2_n$	$I3'_n$	$I4'_n$	$I5_n$	4D Types
0	0	0	0	0	0	0	0	0	(A,A)
			0	0	0	0	0	1	(B,B)
		1	0	0	0	0	1	0	(C,C)
			0	0	0	0	1	1	(D,D)
		8	0	1	0	0	0	0	(A,B)
			0	1	0	0	0	1	(B,A)
		9	0	1	0	0	1	0	(C,D)
			0	1	0	0	1	1	(D,C)
	1	2	0	0	0	1	0	0	(E,E)
			0	0	0	1	0	1	(F,F)
		3	0	0	0	1	1	0	(G,G)
			0	0	0	1	1	1	(H,H)
		10	0	1	0	1	0	0	(E,F)
			0	1	0	1	0	1	(F,E)
		11	0	1	0	1	1	0	(G,H)
			0	1	0	1	1	1	(H,G)
	2	4	0	0	1	0	0	0	(A,C)
			0	0	1	0	0	1	(B,D)
		5	0	0	1	0	1	0	(C,A)
			0	0	1	0	1	1	(D,B)
		12	0	1	1	0	0	0	(A,D)
			0	1	1	0	0	1	(B,C)
		13	0	1	1	0	1	0	(C,B)
			0	1	1	0	1	1	(D,A)
	3	6	0	0	1	1	0	0	(E,G)
			0	0	1	1	0	1	(F,H)
		7	0	0	1	1	1	0	(G,E)
			0	0	1	1	1	1	(H,F)
		14	0	1	1	1	0	0	(E,H)
			0	1	1	1	0	1	(F,G)
		15	0	1	1	1	1	0	(G,F)
			0	1	1	1	1	1	(H,E)
1	4	16	1	0	0	0	0	0	(A,E)
			1	0	0	0	0	1	(B,F)
		17	1	0	0	0	1	0	(C,G)
			1	0	0	0	1	1	(D,H)
		24	1	1	0	0	0	0	(A,F)
			1	1	0	0	0	1	(B,E)
		25	1	1	0	0	1	0	(C,H)
			1	1	0	0	1	1	(D,G)
	5	18	1	0	0	1	0	0	(E,C)
			1	0	0	1	0	1	(F,D)
		19	1	0	0	1	1	0	(G,A)
			1	0	0	1	1	1	(H,B)
		26	1	1	0	1	0	0	(E,D)
			1	1	0	1	0	1	(F,C)
		27	1	1	0	1	1	0	(G,B)
			1	1	0	1	1	1	(H,A)
	6	20	1	0	1	0	0	0	(A,G)
			1	0	1	0	0	1	(B,H)
		21	1	0	1	0	1	0	(C,E)
			1	0	1	0	1	1	(D,F)
		28	1	1	1	0	0	0	(A,H)
			1	1	1	0	0	1	(B,G)
		29	1	1	1	0	1	0	(C,F)
			1	1	1	0	1	1	(D,E)
	7	22	1	0	1	1	0	0	(E,A)
			1	0	1	1	0	1	(F,B)
		23	1	0	1	1	1	0	(G,C)
			1	0	1	1	1	1	(H,D)
		30	1	1	1	1	0	0	(E,B)
			1	1	1	1	0	1	(F,A)
		31	1	1	1	1	1	0	(G,D)
			1	1	1	1	1	1	(H,C)

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lattice with MSED d_0^2 is partitioned into two 4D families $\bigcup_{i=0}^{3} i$ and $\bigcup_{i=4}^{7} i$ with MSED $2d_0^2$. Each 4D family is further partitioned into four 4D sublattices 0, 1, 2, 3, or 4, 5, 6, 7, with MSED $4d_0^2$. A second constituent 4D rectangular lattice formed by the third and fourth constituent 2D rectangular lattices is similarly partitioned.

Sixty-four 8D types are then formed, each corresponding to a pair of 4D sublattices and denoted as (0,0), (0,1), $\cdots$, and (7,7). Using the general principles described earlier, those 64 8D types may be grouped into 16 8D sublattices with MSED $4d_0^2$ and denoted as 0, 1, $\cdots$, and 15, as shown in Table II. Those 16 8D sublattices may be further grouped into two 8D families $\bigcup_{i=0}^{7} i$ and $\bigcup_{i=8}^{15} i$ with MSED $2d_0^2$.

The advantages of grouping multidimensional types into sublattices are clear in this example. Without that grouping, the 8D rectangular lattice with MSED d_0^2 might have been partitioned into 256 sublattices with MSED $4d_0^2$, each sublattice being an 8D subtype formed by concatenating 2D sublattices of Figs. 1 or 2, and denoted as (A, A, A, A), $(A, A, A, B), \cdots$, or (D, D, D, D). The task of constructing a trellis code using those 256 sublattices and the corresponding maximum-likelihood decoding would be extremely difficult if not impossible.

There are other ways to partition the 8D rectangular lattice into 16 8D sublattices to give the same distance properties as the earlier partitioning. However, the earlier partitioning has the special property that each 8D sublattice is invariant under each rotation corresponding to a phase ambiguity (90°, 180°, or 270°) of the lattice. With that property, the construction of rotationally invariant trellis codes using those 8D sublattices does not need to consider such rotations and is much simplified.

Based on the earlier partitioning of the 8D rectangular lattice, it is straightforward to show that the 16D rectangular lattice with MSED d_0^2 may be partitioned into two families with MSED $2d_0^2$, and each family may be further partitioned into 16 sublattices with MSED $4d_0^2$.

To partition a multidimensional rectangular lattice with MSED d_0^2 into sublattices with MSED greater than $4d_0^2$, a partitioning of each constituent 2D rectangular lattice into more than four 2D sublattices should be used. Table III gives a partitioning of the 4D rectangular lattice with MSED d_0^2 into 32 sublattices with MSED $8d_0^2$, based on an eight-sublattice partitioning of the 2D rectangular lattice shown in Fig. 3 (note that the rectangular lattice in the figure is rotated by 45°).

The relationships between the sublattices, subfamilies, and families of the 4D rectangular lattice shown in Tables I or III with the densest 4D lattice D_4 are now exploited. A translation of the 4D lattice D_4 may be defined as 4D sublattice 0 of Table I [3], [9]. With that definition of D_4, it is easy to see that each of the 4D sublattices, subfamilies, and families of Tables I or III may be interpreted as a translated, rotated, or scaled version of D_4. The partitioning of the 4D rectangular lattice may then be expressed as in Fig. 4. From that figure, we see that each time the intrasublattice (a D_4 lattice) MSED is doubled, the number of 4D sublattices is multiplied by four. Extensions to finer partitionings of the 4D rectangular lattice become obvious. Fig. 4 also says that a 4D lattice D_4 with MSED $2d_0^2$ may be partitioned into 16 sublattices with MSED $8d_0^2$, based on the eight-sublattice partitioning of its constituent 2D rectangular lattice shown in Fig. 3.

Similar relationships are exploited between the sublattices of the 8D rectangular lattice of Table II and the densest 8D lattice E_8. A translation of E_8 may be defined as 8D sublattice 0 of Table II [3], [6], [9]. With this definition of E_8, it is easy to see that other 8D sublattices of Table II are also translated or rotated versions of E_8. The partitioning of the 8D rectangular lattice of Table II may therefore be expressed as in Fig. 5, where it is also shown that each 8D family is an 8D lattice D_8 [9].

A finer partitioning of the 8D rectangular lattice with MSED d_0^2 into sublattices with MSED $8d_0^2$ will show that an 8D lattice E_8 with MSED $4d_0^2$ may be partitioned into 16 sublattices with MSED $8d_0^2$, based on the eight-sublattice partitioning of its constituent 2D rectangular lattice shown in Fig. 3. Each sublattice of E_8 can be shown to be another translated, rotated, or scaled version of E_8. The partitioning of E_8 is also shown in Fig. 5. From that figure, we see that each time the intrasublattice (an E_8 lattice) MSED is doubled, the number of 8D sublattices is multiplied by 16. Extensions to finer partitionings of the

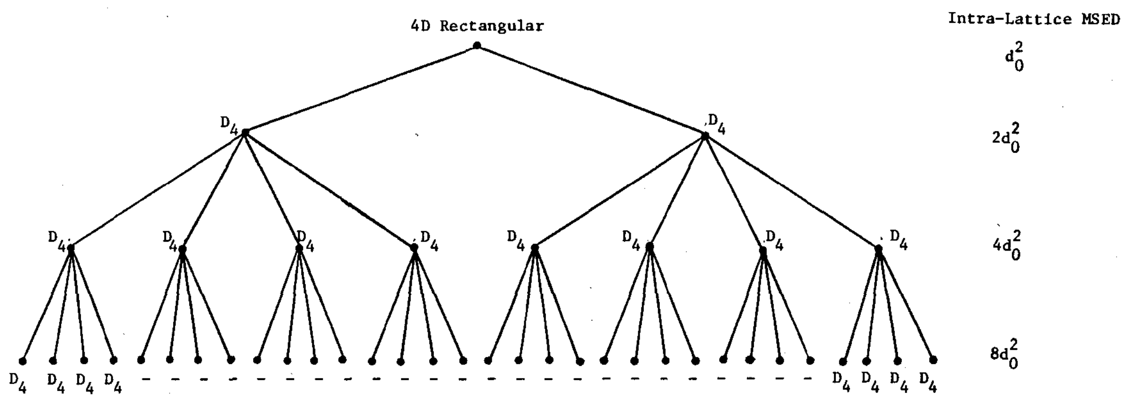

Fig. 4. Partitioning of 4D rectangular lattice.

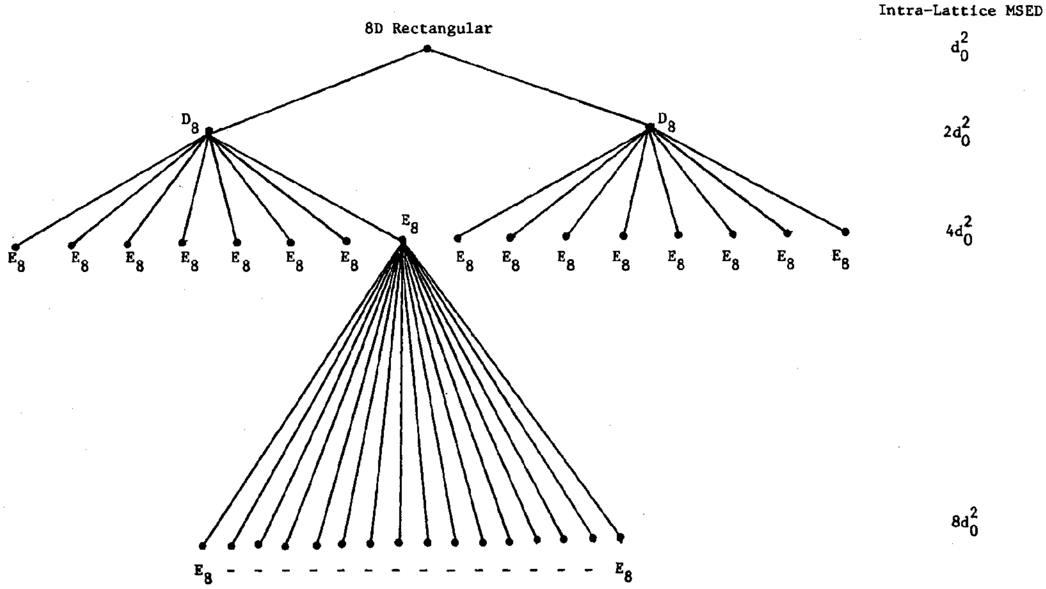

Fig. 5. Partitioning of 8D rectangular lattice.

8D rectangular lattice or the densest 8D lattice E_8 become obvious.

Finally, we define an 8D lattice DE_8 as the union of an E_8 and a rotated version of that E_8. The E_8 is 8D sublattice 0 of Table II. Furthermore, the rotated version of that E_8 is obtained by rotating the third and fourth constituent 2D points of each 8D point in that E_8 by 90° clockwise, which is 8D sublattice 1 of Table II. (Such a lattice has not to our knowledge appeared previously in the coding literature.) The MSED of the lattice DE_8 is thus $2d_0^2$. This lattice may be partitioned into two 8D families with MSED $4d_0^2$. Each family is a version of E_8 which may be further partitioned into 16 sublattices with MSED $8d_0^2$. We will use DE_8 and this 32-sublattice partitioning in a later coded-modulation scheme.

III. Construction of Multidimensional Constellations

To transmit Q information bits per signaling interval using a $2N$-dimensional trellis code of rate $m/m+1$, a $2N$-dimensional constellation of 2^{NQ+1} points is needed. In this section, we show how to construct such finite constellations from various infinite $2N$-dimensional lattices.

For small values of $NQ+1$ and a communication system where additive Gaussian noise is the only impairment, the constellation may be constructed to keep the average power as small as possible. However, for large values of $NQ+1$ or a communication system where other impairments such as linear or nonlinear distortion or phase jitter are also present, of which voiceband data transmission is an example, it is important to construct the constellation so that 1) the complicated mapping between the $NQ+1$ bits and the $2N$-dimensional constellation may be converted to N simple constituent 2D constellation mappings; 2) the size of the constituent 2D constellations is kept as small as possible; and 3) the peak-to-average power ratio is also kept as small as possible. The construction we give is similar to that used in [3] for transmitting a nonintegral number of bits per signaling interval in an uncoded scheme.

As we shall see, using this construction, the size of the constituent 2D constellations of a multidimensional constellation may be significantly smaller than that of a corresponding 2D trellis-coded modulation scheme. There is also essentially no penalty in peak-to-average power ratio from the use of a multidimensional constellation. With all of these desirable characteristics, the construction leads the way to practical applications of multidimensional trellis-coded modulation.

To appreciate the advantages of this construction, we will focus on the case where Q is equal to seven (unless otherwise specified). Such a number of bits per signaling interval may be used in voiceband modems at data rates higher than 14.4 kbit/s.

To construct a 4D constellation of 2^{15} points from the 4D rectangular lattice, we first construct its constituent 2D constellations. Fig. 1 shows a 192-point 2D constellation partitioned into four subsets A, B, C, and D. The 2D constellation includes the 128-point cross constellation (128-CR) located within the boundary shown, which is typically used in an uncoded scheme for transmitting seven bits per signaling interval. Those 128 points are called inner points. The 2D constellation also includes an outer group of 64 points, half as many as in the inner group. The outer points are selected as close to the origin as possible while satisfying the following two requirements. First, each subset A, B, C, or D has the same number of outer points. Second, if an outer point is rotated by 90°, 180°, or 270°, another outer point is obtained. The first requirement is necessary to convert the 4D constellation mapping into a pair of 2D constellation mappings. The second require-

ment preserves the symmetries of the lattice in the constellation. The two requirements should also be satisfied by the inner points, as 128-CR does.

The 4D constellation of 2^{15} points is then constructed by concatenating a pair of the 192-point 2D constellations, and excluding those 4D points whose corresponding pair of 2D points are both outer points. The average power of the 4D constellation may be determined as follows. For each constituent 192-point 2D constellation, the inner group is used three times as often as the outer group. The average power of the 4D constellation, which is also the average power of each constituent 192-point 2D constellation in this case, is thus $3/4$ times the average power of the inner points plus $1/4$ times the average power of the outer points. It is then straightforward to show that the average power of the 4D constellation is $28.0625d_0^2$. The peak power of the 4D constellation, which is also the peak power of the constituent 192-point 2D constellations, is $60.5d_0^2$. The peak-to-average power ratio of the 4D constellation is therefore 2.16, smaller than the peak-to-average power ratio, 2.33, of the 64-point 2D square constellation commonly used in an uncoded scheme for transmitting six bits per signaling interval.

The partitioning of the 4D rectangular lattice of Table I underlies the partitioning of this 4D constellation. From now on, for notational convenience, when we say that a constellation is of a certain type, we mean that the constellation is derived from a lattice of that type. For example, when we say a 4D rectangular constellation, we mean a 4D constellation derived from the 4D rectangular lattice. Furthermore, we will carry over the terminology used in the partitioning of a lattice, such as family, subfamily, type, and subtype, to the partitioning of a constellation derived from that lattice. The terminology "sublattice" will be replaced by "subset" to be consistent with previous work on partitioning 2D constellations.

In general, to transmit Q information bits per signaling interval using a rate-$m/m+1$ trellis code with a $2N$-dimensional rectangular constellation, where N is a power of two, the $2N$-dimensional constellation of 2^{NQ+1} points is constructed as follows. The first step is to obtain a constituent 2D rectangular constellation. The 2D constellation is divided into two groups, an inner group and an outer group. The number of points in the inner group is 2^Q, the same as that in the corresponding uncoded scheme. The number of points in the outer group is $1/N$ of that in the inner group. The inner group is selected first from the rectangular lattice so that the average power of the inner group is kept as small as possible. The outer group is selected from the rest of the rectangular lattice so that the average power of the outer group is minimized. The inner and outer groups must satisfy two requirements: first, each subset, obtained by partitioning the 2D constellation in accordance with the partitioning of the $2N$-dimensional constellation as described in the last section, has the same number of points in each group as other subsets; and second, each group is invariant under 90°, 180°, and 270° rotations. (Note that when a 2D rectangular constellation is partitioned into four subsets as in Fig. 1, satisfaction of the second requirement guarantees that the first requirement is also satisfied. However, this may not be the case when a 2D rectangular constellation is partitioned into more than four subsets.)

The $2N$-dimensional constellation of 2^{NQ+1} points is then constructed by concatenating N such 2D constellations, and excluding those $2N$-dimensional points corresponding to more than one 2D outer point. There are 2^{NQ} $2N$-dimensional points comprising only 2D inner points and 2^{NQ} $2N$-dimensional points comprising one 2D outer point. For each constituent 2D constellation, the inner group is used $2N-1$ times as often as the outer group. The average power of the $2N$-dimensional constellation, which is also the average power of each constituent 2D constellation in this case, is thus $(2N-1)/2N$ times the average power of the inner points plus $1/2N$ times the average power of the outer points.

Following the general principles described, an 8D rectangular constellation of 2^{29} points may be constructed from the 160-point 2D constellation shown in Fig. 2. The 2D constellation is partitioned into four subsets A, B, C, and D in accordance with the 16-subset partitioning of the 8D rectangular constellation (see Table II). The inner group is still 128-CR. The outer group has 32 points, only a quarter as many as in the inner group. The 8D constellation is formed by concatenating four such 160-point 2D constellations, and excluding those 8D points corresponding to more than one 2D outer point. The average power of this 8D constellation is $23.59375d_0^2$ with peak-to-average power ratio 2.14.

One advantage of using trellis coding with a multidimensional rectangular constellation instead of a 2D constellation becomes clear. It not only reduces the number of redundant bits but also reduces the size of the constituent 2D constellations. This is desirable especially when the size of the 2D constellation for the corresponding uncoded scheme, such as 128-CR, is already very large.

Using a multidimensional constellation has another advantage. It is easy to transmit a nonintegral number of information bits per signaling interval in such a constellation. Nonintegral numbers of bits per signaling interval poses a serious problem to any 2D modulation scheme. An unnecessarily large 2D constellation with a large peak-to-average power ratio is often required. This issue may be eliminated in a multidimensional constellation. For example, to transmit 7-1/4 information bits per signaling interval using a rate $m/m+1$ trellis code with an 8D rectangular constellation partitioned in accordance with Table II, the 8D constellation of 2^{30} points may be constructed from the 192-point 2D constellation of Fig. 1 as follows. A 4D constellation of 2^{15} points is first constructed from the 192-point 2D constellation of Fig. 1 as before. The 8D constellation of 2^{30} points is then formed by simply concatenating a pair of such 4D constellations. The average power and peak-to-average power ratio of this 8D constellation are $28.0625d_0^2$ and 2.16, respectively, the same as those of the constituent 4D constellations. The increase in

the average power of this 8D constellation from that of the previous 8D constellation of 2^{29} points is 0.75 dB, as one would expect based on the expectation that an additional information bit per signaling interval costs about an additional 3 dB of signal power [3]. Generalization of this example to other nonintegral numbers of bits or other multidimensional constellations will be reported in a companion paper.

In the remainder of this section, we shall briefly describe a few more multi-dimensional constellations to be used in the later coded modulation schemes. To partition a 4D rectangular constellation into 32 subsets as shown in Table III, each constituent 2D constellation is partitioned into eight subsets. Fig. 3 shows a 192-point 2D constellation with such a partitioning. The constellation happens to be the same as that of Fig. 1 except for a 45° rotation. A pair of such 2D constellations may be used to construct a 4D rectangular constellation of 2^{15} points with the same average power and peak-to-average power ratio as before.

A 16D rectangular constellation of 2^{57} points may be constructed from a 144-point 2D constellation with 128-CR as its inner group and only 16 points in its outer group. The average power of the 16D constellation can be shown to be $21.875d_0^2$ with peak-to-average power ratio 2.03.

In the case where a multidimensional constellation is derived from a nonrectangular lattice such as D_4, E_8, or DE_8, the construction of the nonrectangular constellation is slightly different from that of a rectangular constellation. The difference occurs because when the multidimensional nonrectangular constellation is constructed from its constituent 2D rectangular constellations, the concatenation of 2D points must be a valid point of the nonrectangular lattice.

With this difference, it can be shown that a 4D constellation D_4 of 2^{15} points may be constructed by concatenating a pair of 256-point 2D rectangular constellations. The 4D constellation has an average power $40.6875d_0^2$ and peak-to-average power ratio 1.93.

Similarly, a 320-point 2D rectangular constellation may be used to construct an 8D constellation E_8 of 2^{29} points with average power $47.133d_0^2$ and peak-to-average power ratio 2.17. The same 256-point 2D rectangular constellation used for the 4D constellation D_4 may be used to construct an 8D constellation DE_8 of 2^{29} points with the same average power and peak-to-average power ratio as for the 4D constellation D_4. Note that using an 8D constellation DE_8 rather than E_8 reduces both the size of the constituent 2D constellation and the average power of the 8D constellation.

IV. Trellis-Coded Modulation with Multidimensional Constellations

To send Q information bits per signaling interval using a rate-$m/m+1$ trellis code with a $2N$-dimensional constellation partitioned into 2^{m+1} subsets, m of the NQ information bits arriving in each block of N signaling intervals enter the trellis encoder, and the resulting $m+1$ coded bits specify which $2N$-dimensional subset is to be used. The remaining information bits specify which point from the selected $2N$-dimensional subset is to be transmitted.

In this section, we show how to construct rate-$m/m+1$ trellis codes with various partitionings of $2N$-dimensional constellations and how to select a point from a $2N$-dimensional subset; or, more generally, how to map the $NQ+1$ trellis-encoded or nontrellis-encoded bits into a $2N$-dimensional constellation. The $2N$-dimensional constellation mapping is converted to N constituent 2D constellation mappings with the assistance of a bit converter and a block encoder.

A number of trellis codes have been constructed and evaluated in terms of coding gain, error coefficient, transparency to phase ambiguities, size of constituent 2D constellations, peak-to-average power ratio, and complexity. In particular, a 16-state code with a 4D rectangular constellation partitioned as in Table I is shown in Section IV-A. Section IV-B shows a 64-state code with an 8D rectangular constellation partitioned as in Table II. These two codes are optimal in the sense that, given the constellation and its partitioning, each code achieves both the largest possible coding gain and the smallest possible error coefficient with the smallest number of states. Both codes are transparent to all phase ambiguities (90°, 180°, and 270°) of their constellations.

To increase the coding gain further using a 4D rectangular constellation, a finer partitioning of the 4D constellation as shown in Table III should be used. Section IV-C shows a 64-state code with this partitioning of the 4D rectangular constellation. This is the smallest number of states that can be used to realize the larger coding gain promised by the finer partitioning of the 4D constellation. This 64-state code is also transparent to all phase ambiguities of the constellation.

In Section IV-D, we extend our study to other codes with 4D, 8D, and 16D rectangular constellations, D_4, E_8, and DE_8. Again, as in the previous section, we will focus on the case where the number Q of information bits transmitted per signaling interval is seven unless otherwise specified. The seven information bits arriving in the current signaling interval n are denoted as $I1_n$, $I2_n, \cdots$, and $I7_n$.

A. 16-State Code with 4D Rectangular Constellation

A rate-2/3, 16-state code with a 4D rectangular constellation of 2^{15} points is shown in Fig. 6. The 4D constellation is constructed from the 192-point 2D constellation of Fig. 1 as in the last section and is partitioned into eight subsets as in Table I. The three output bits $Y0_n$, $I1_n$, and $I2'_n$ of the trellis encoder are associated with the 4D subsets in accordance with Table I.

If we denote the current and next states of the trellis encoder as $W1_pW2_pW3_pW4_p$, $p=n$ and $n+2$, the trellis diagram is as shown in Fig. 7. The association of 4D subsets with the state transitions of Fig. 7 satisfies the following three requirements: 1) the 4D subsets associated

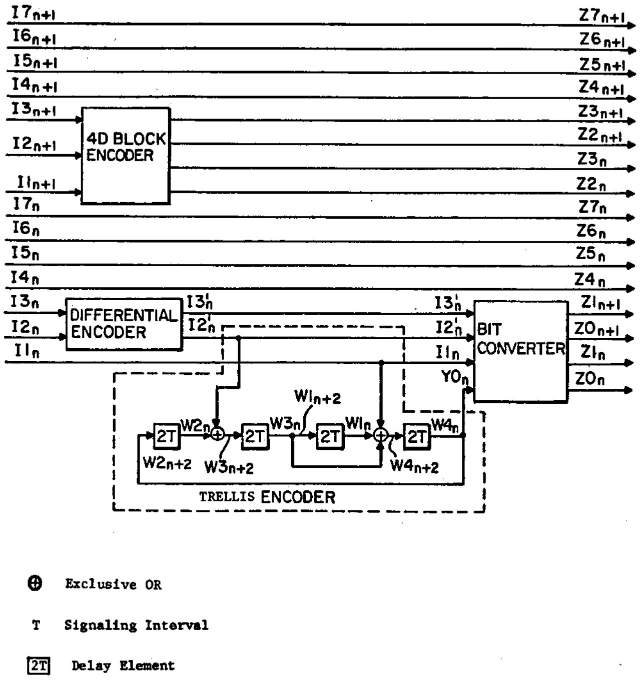

Fig. 6. 16-state code with 4D rectangular constellation.

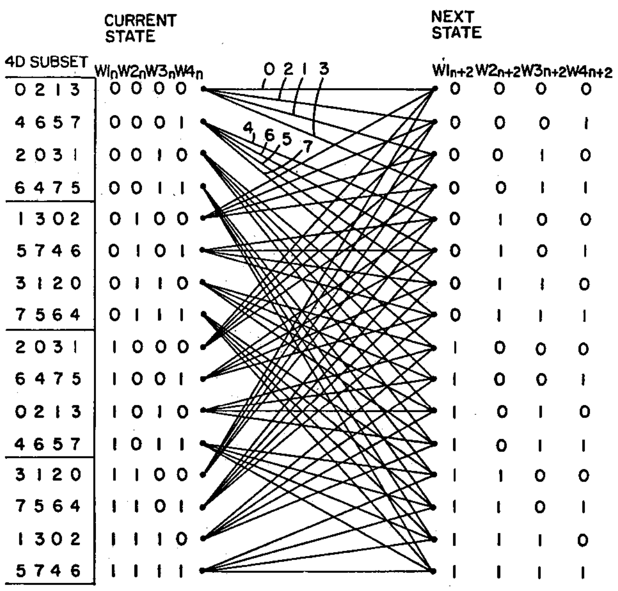

Fig. 7. Trellis diagram of 16-state code of Fig. 6.

with the transitions leading from a state are different from each other and belong to the same 4D family $\cup_{i=0}^{3} i$ or $\cup_{i=4}^{7} i$ (see Section II), and likewise for the 4D subsets associated with the transitions leading to a state; 2) the MSED between two allowed sequences of 4D subsets corresponding to two distinct trellis paths is larger than $4d_0^2$, which is the MSED of each 4D subset; and 3) a one-to-one function F that maps each state of the trellis encoder into another state may be defined so that the following statement is valid. Denote X as the 4D subset associated with the transition from a current state i to a next state j, and Y as the 4D subset obtained when X is rotated by 90° clockwise. Then Y is associated with the transition from the current state $F(i)$ to the next state $F(j)$. The function F for this code is

$$F: W1_pW2_pW3_pW4_p \rightarrow \overline{W1_p}W2_p\overline{W3_p}W4_p$$

where an overbar denotes inversion.

That the second requirement above is satisfied may be seen as follows. Referring to Fig. 7, for each current state $W1_nW2_nW3_nW4_n$, the four possible next states are $W3_nW4_nX1X2$, where $X1X2 = 00$, 01, 10, or 11. All transitions originating from even-numbered states (states with $W4_n$ equal to zero) are associated with 4D subsets from the first 4D family $\cup_{i=0}^{3} i$, while all transitions originating from odd-numbered states (states with $W4_n$ equal to one) are associated with 4D subsets from the second 4D family $\cup_{i=4}^{7} i$. Furthermore, if Y is the 4D subset associated with the transition from a current state $W1_nW2_nW3_nW4_n$ to an even-numbered (or odd-numbered) next state, then Y is also the 4D subset associated with the transition from the current state $W1_nW2_n\overline{W3_n}W4_n$ to an odd-numbered (or even-numbered) next state.

The first requirement guarantees that the MSED between any two allowed sequences of 4D points is $4d_0^2$. The coding gain of the code over the uncoded 128-CR therefore is

$$10\log_{10}\left(\frac{4d_0^2}{28.0625d_0^2}\Big/\frac{d_0^2}{20.5d_0^2}\right) = 4.66 \text{ dB},$$

where $28.0625d_0^2$ is the average power of the 4D constellation as determined in the last section, and $20.5d_0^2$ is the average power of 128-CR. This is also the largest possible coding gain that can be achieved with the partitioning of the 4D rectangular constellation of Table I. This coding gain may be viewed as the combination of a gain of 6.02 dB from the trellis code if the 4D constellation were not expanded from 2^{14} to 2^{15} points, and a loss of 1.36 dB due to that expansion. The expansion loss is less than the 3 dB loss of a 2D rate-$m/m+1$ trellis code, as promised by the use of a 4D constellation.

The second requirement above eliminates MSED error events which differ in more than one 4D point from a given sequence of 4D points. The error coefficient of the code is thus minimized to 24 per 4D point (equivalent to 12 per 2D point), which is the number of nearest neighbors to any point in the same 4D subset (a D_4 lattice). Taking into account the boundary effect of the finite constellation would reduce this value.

The third requirement guarantees that the code can be made transparent to all phase ambiguities (90°, 180°, and 270°) of the constellation. Since the same 4D subset is obtained when a 4D subset is rotated by 180°, the construction of the trellis code needs to take into account only 90° rotation. The 270° rotation is then taken care of automatically.

We now show how to map the three trellis-encoded bits and the remaining 12 non-trellis-encoded information bits into the 4D constellation. Referring to Table I, after using the three trellis-encoded bits to specify a 4D subset, a

fourth nontrellis-encoded information bit $I3'_n$ is used to specify a 4D type within the 4D subset. To make the scheme transparent to all phase ambiguities of the constellation, the association of the three trellis-encoded bits $Y0_n$, $I1_n$, and $I2'_n$, and the fourth uncoded bit $I3'_n$, with 4D types is done as follows. For each pattern $Y0_nI1_nI2'_nI3'_n$, denote X as the associated 4D type. Denote $X1$, $X2$, and $X3$ as the 4D types obtained when the 4D type X is rotated by 90°, 180°, and 270° clockwise, respectively. Denote $S3_1S2_1$, $S3_2S2_2$, and $S3_3S2_3$ as the bit pairs obtained when the bit pair $I3'_nI2'_n$ is advanced by one, two, and three positions, respectively, in a circular sequence 00, 01, 10, 11. Then the 4D types associated with the bit patterns $Y0_nI1_nS2_1S3_1$, $Y0_nI1_nS2_2S3_2$, and $Y0_nI1_nS2_3S3_3$ are $X1$, $X2$, and $X3$, respectively.

As a first step of the 4D constellation mapping, a bit converter converts the four bits $Y0_n$, $I1_n$, $I2'_n$, and $I3'_n$ into two pairs of selection bits, $Z0_nZ1_n$ and $Z0_{n+1}Z1_{n+1}$, which are used to select the pair of 2D subsets corresponding to the 4D type. With the correspondence between the bit pair $Z0_pZ1_p$ and 2D subsets A, B, C, and D as shown in Table IV, the operation of the bit converter is shown in Table I.

TABLE IV
CORRESPONDENCE BETWEEN $Z0_pZ1_p$ AND FOUR 2D SUBSETS

2D Subset	$Z0_pZ1_p$
A	00
B	01
C	10
D	11

A 4D block encoder then takes three of the remaining eleven uncoded information bits, $I1_{n+1}$, $I2_{n+1}$, and $I3_{n+1}$, and generates two pairs of selection bits, $Z2_nZ3_n$ and $Z2_{n+1}Z3_{n+1}$ in accordance with Table V. Each of the bit pairs can assume any of the values 00, 01, or 10, but they cannot both assume the value 10. The first pair $Z2_nZ3_n$ will be used to select the inner group or outer group of the first selected 2D subset, and likewise for the second pair with respect to the second 2D subset. The inner group is organized into two halves. If the bit pair is 00, one-half of the inner group is selected; if the bit pair is 01, the other half of the inner group is selected; otherwise the outer group is selected.

TABLE V
4D BLOCK ENCODER

$I1_{n+1}$	$I2_{n+1}$	$I3_{n+1}$	$Z2_n$	$Z3_n$	$Z2_{n+1}$	$Z3_{n+1}$
0	0	0	0	0	0	0
0	0	1	0	0	0	1
0	1	0	0	0	1	0
0	1	1	0	1	1	0
1	0	0	1	0	0	0
1	0	1	1	0	0	1
1	1	0	0	1	0	0
1	1	1	0	1	0	1

There are 16 2D points in the outer group or in either half of the inner group of a 2D subset, and eight uncoded information bits remain for selecting from among those 2D points. Those eight bits are taken in two groups of four bits each and are renamed as $Z4_pZ5_pZ6_pZ7_p$, $p = n$ and $n+1$. The first group $Z4_nZ5_nZ6_nZ7_n$ is used to select a 2D point from the previously selected outer group or the selected half of the inner group of the first 2D subset, and likewise for the second group $Z4_{n+1}Z5_{n+1}Z6_{n+1}Z7_{n+1}$.

To make the scheme transparent to all phase ambiguities of the constellation, the association of the bit group $Z2_pZ3_pZ4_pZ5_pZ6_pZ7_p$, $p = n$ or $n+1$, with 2D points should be such that the same bit pattern of the group is associated with each of the four 2D points which can be obtained from each other through 90° rotations. In Fig. 1, each point in subset A is associated with a bit pattern of $Z2_pZ3_pZ4_pZ5_pZ6_pZ7_p$. The bit pattern associated with points in other subsets can be obtained by following the above rule.

To summarize, the bit converter and the 4D block encoder take the three trellis-encoded bits and the 12 remaining uncoded information bits and produce two groups of eight selection bits each, $Z2_pZ3_pZ4_pZ5_pZ6_pZ7_pZ0_pZ1_p$, $p = n$ and $n+1$. The first group is then used to address a 2D mapping table to obtain a first 2D point. The table may be constructed from Fig. 1 and Table IV. The second group addresses the same 2D mapping table to obtain the second 2D point. The 4D point corresponding to the pair of 2D points is the one selected for transmission.

That the scheme is transparent to all the phase ambiguities of the constellation may be seen as follows. If we translate a sequence of the bit pairs $I3'_nI2'_n$ appearing at the inputs of the trellis encoder and the bit converter all by the same number of positions, one, two, or three, in a circular sequence, 00, 01, 10, 11, then the sequence of 2D points produced by the 4D constellation mapping procedure will be rotated by 90°, 180°, and 270° clockwise, respectively. Therefore, a differential encoder of the form

$$I3'_nI2'_n = (I3'_{n-2}I2'_{n-2} + I3_nI2_n) \bmod 100_{\text{base2}}$$

in Fig. 6 and a corresponding differential decoder of the form

$$I3_nI2_n = (I3'_nI2'_n - I3'_{n-2}I2'_{n-2}) \bmod 100_{\text{base2}}$$

at the output of the trellis decoder will remove all the phase ambiguities of the constellation.

Two general principles in constructing a trellis code with a multidimensional constellation may be extracted here. The first principle says that the intersubset MSED of the multidimensional subsets associated with transitions originating from each state of the trellis encoder should be kept as large as possible, and likewise for the multidimensional subsets associated with transitions leading to each state. This principle is also used in [1] for constructing a 2D trellis code.

The second principle says that for each of those phase ambiguities of the constellation such that the multidimensional subsets are not invariant under the corresponding

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rotations, it should be possible to define a one-to-one function F which maps each state of the trellis encoder into another state so that the following statement is valid. Let X be the multidimensional subset associated with the transition from a current state i to a next state j. Let Y be the multidimensional subset obtained when X is rotated by a number of degrees corresponding to that phase ambiguity. Then Y is the multidimensional subset associated with the transition from the current state $F(i)$ to the next state $F(j)$. The second principle is also used in [2] for constructing a rotationally invariant 2D trellis code.

B. 64-State Code with 8D Rectangular Constellation

A rate-3/4, 64-state code with an 8D rectangular constellation of 2^{29} points is shown in Fig. 8. The 8D constellation is constructed from the 160-point 2D constellation of Fig. 2 as in the last section and is partitioned into sixteen subsets as in Table II. The association of the four trellis-encoded bits $Y0_n$, $I1_n$, $I2_n$, and $I3_n$ with the 8D subsets is also shown in Table II.

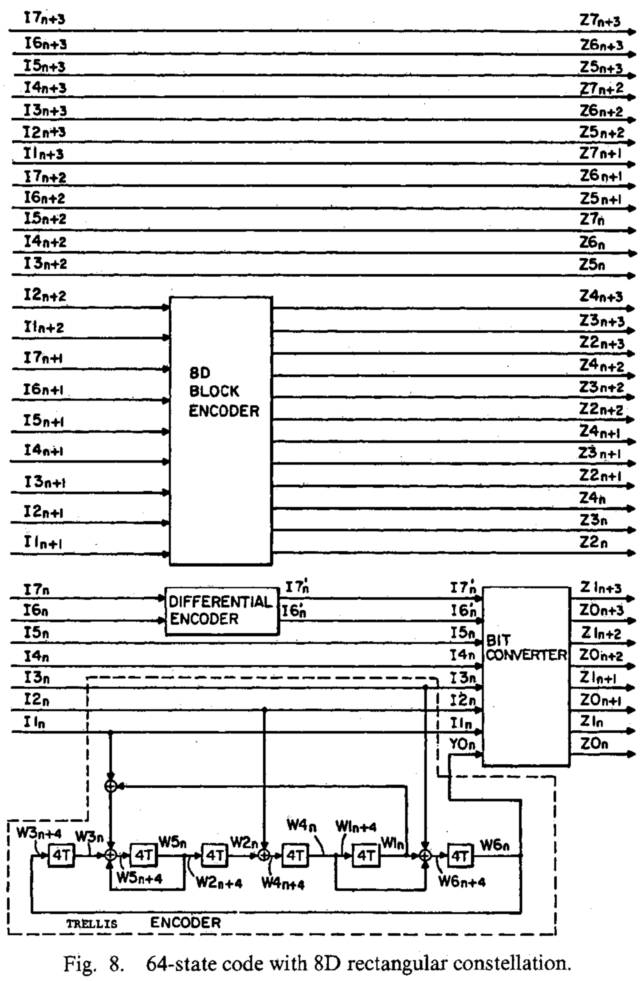

Fig. 8. 64-state code with 8D rectangular constellation.

The association of the 8D subsets with the state transitions of the trellis code satisfies the first general principle described at the end of the last subsection. Therefore the MSED between two allowed sequences of 8D points is $4d_0^2$, and the coding gain over the uncoded 128-CR is

$$10\log_{10}\left(\frac{4d_0^2}{23.59375d_0^2}\Big/\frac{d_0^2}{20.5d_0^2}\right)=5.41\text{ dB}$$

where $23.59375d_0^2$ is the average power of the 8D constellation as determined in the last section. This is also the largest possible coding gain that can be achieved with the partitioning of the 8D rectangular constellation of Table II. This coding gain may be segregated into two parts, a gain of 6.02 dB from the trellis code if the 8D constellation were not expanded from 2^{28} to 2^{29} points, and a loss of 0.61 dB due to that expansion. This expansion loss is less than the 1.36 dB loss for the 4D code in the last subsection.

There is no need to consider any of the phase ambiguities (90°, 180°, and 270°) of the 8D rectangular constellation in the construction of a rotationally invariant trellis code with the partitioning of the constellation of Table II because each 8D subset is invariant under rotations corresponding to those phase ambiguities.

The association of the 8D subsets with the state transitions also meets the following requirement. The MSED between two valid sequences of 8D subsets corresponding to two distinct trellis paths is larger than $4d_0^2$, which is the MSED of each 8D subset. The error coefficient of the code is thus minimized to 240 per 8D point (equivalent to 60 per 2D point), which is the number of nearest neighbors to any point in the same 8D subset (an E_8 lattice).

Referring to Fig. 8, after an 8D subset is selected by the four trellis-encoded bits, another four nontrellis-encoded information bits $I4_n$, $I5_n$, $I6_n'$, and $I7_n'$ are used to select an 8D subtype within the 8D subset (see Section II). To make the scheme transparent to all phase ambiguities of the constellation, the association of the four uncoded information bits with the 8D subtypes meets the following requirement. For each 8D subset, let X be the 8D subtype associated with a bit pattern of $I4_nI5_nI6_n'I7_n'$. Let $X1$, $X2$, and $X3$ be the 8D subtypes obtained when X is rotated by 90°, 180°, and 270° clockwise, respectively. Denote $S6_1S7_1$, $S6_2S7_2$, and $S6_3S7_3$ as the bit pairs obtained when the bit pair $I6_n'I7_n'$ is advanced by one, two, and three positions, respectively, in a circular sequence 00, 01, 10, 11. Then the 8D subtypes associated with the bit patterns $I4_nI5_nS6_1S7_1$, $I4_nI5_nS6_2S7_2$, and $I4_nI5_nS6_3S7_3$ are $X1$, $X2$, and $X3$, respectively. The 8D subtype selection procedure shown in Fig. 9 meets the above requirement.

To map the four trellis-encoded bits and the 25 remaining nontrellis-encoded information bits into the 8D constellation, a bit converter and an 8D block encoder are used to convert those 29 bits into four groups of eight selection bits each, $Z2_pZ3_pZ4_pZ5_pZ6_pZ7_pZ0_pZ1_p$, $p = n$, $n+1$, $n+2$, and $n+3$. Each group is then used to address the same 2D mapping table to obtain a 2D point. The 8D point corresponding to those four 2D points is the one selected for transmission. The 2D mapping table may be constructed from Fig. 2 and Table IV. In Fig. 2, the same six-bit value is associated with each of the four points

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STEP I:
USE $Y0_n\ I1_n\ I2_n\ I3_n$ TO OBTAIN AN 8D SUBTYPE

$Y0_n$	$I1_n$	$I2_n$	$I3_n$	8D SUBTYPE
0	0	0	0	(A A A A)
0	0	0	1	(A A C C)
0	0	1	0	(A A A B)
0	0	1	1	(A A C D)
0	1	0	0	(A C A C)
0	1	0	1	(A C C B)
0	1	1	0	(A C A D)
0	1	1	1	(A C C A)
1	0	0	0	(A A A C)
1	0	0	1	(A A C B)
1	0	1	0	(A A A D)
1	0	1	1	(A A C A)
1	1	0	0	(A C A A)
1	1	0	1	(A C C C)
1	1	1	0	(A C A B)
1	1	1	1	(A C C D)

STEP 2:
ROTATE THE $\left\{\begin{matrix}\text{3RD \& 4TH}\\ \text{2ND \& 4TH}\\ \text{2ND \& 3RD}\end{matrix}\right\}$ 2D SUBSETS OF THE 8D SUBTYPE BY 180° IF $I4_nI5_n = \left\{\begin{matrix}01\\10\\11\end{matrix}\right\}$

STEP 3:
ROTATE ALL FOUR 2D SUBSETS OF THE 8D SUBTYPE OBTAINED IN STEP 2 BY
$\left\{\begin{matrix}90°\\180°\\270°\end{matrix}\right\}$ CLOCKWISE IF $I6'_nI7'_n = \left\{\begin{matrix}01\\10\\11\end{matrix}\right\}$

Fig. 9. 8D subtype selection procedure for 64-state code of Fig. 8.

which can be obtained from each other through 90° rotations.

The table for the bit converter can be obtained from Fig. 9 and Table IV. The operation of the 8D block encoder is shown in Fig. 10. It takes nine uncoded information bits and generates four groups of three selection bits each. Each bit group can assume any of the values 000, 001, 010, 011, and 100, but at most one of the bit groups can assume the value 100. Each bit group is used to select the inner or outer group of points of a 2D subset corresponding to the previously selected 8D subtype. If the value of the bit group is 000, 001, 010, or 011, a quarter of the inner group of points is selected; if it is 100, the outer group of points is selected.

The differential encoder in Fig. 8 has the form

$$I6'_nI7'_n = (I6'_{n-4}I7'_{n-4} + I6_nI7_n) \bmod 100_{\text{base2}}.$$

It is straightforward to show that the scheme in Fig. 8 is transparent to all phase ambiguities of the constellation.

C. 64-State Code with 4D Rectangular Constellation

To increase the coding gain further using a 4D rectangular constellation, a finer partitioning of the 4D constellation as shown in Table III should be used. A rate-4/5, 64-state code with a 4D rectangular constellation of 2^{15} points is shown in Fig. 11. The 4D constellation is constructed from the 192-point 2D constellation of Fig. 3 as in the last section. The association of the five trellis-encoded bits $Y0_n$, $I1_n$, $I2_n$, $I3'_n$, and $I4'_n$, and a sixth nontrellis-encoded information bit, $I5_n$, with the 4D types is shown in Table III. The 4D constellation mapping is converted into a pair of constituent 2D constellation mappings in a manner similar to that in the previous two subsections.

The MSED between two allowed sequences of 4D points of this code may be derived from the trellis diagram of the code. The trellis diagram satisfies the first general principle described in Section IV-A. The MSED of the code therefore is at least $4d_0^2$. For each current state $W1_nW2_nW3_nW4_nW5_nW6_n$, the sixteen possible next states are $W5_nW6_nX1X2X3X4$ where $X1$, $X2$, $X3$, and $X4$ are binary variables. All the transitions originating from even-numbered states (states with $W6_n$ equal to 0) are associated with 4D subsets from 4D family 0 (see Table III). All the transitions originating from odd-numbered states (states with $W6_n$ equal to one) are associated with 4D subsets from 4D family 1. Denote Y as the 4D subset associated with the transition from a current state $W1_nW2_nW3_nW4_nW5_nW6_n$ to a next state $W5_nW6_nX1X2X3X4$. Then Y and the three 4D subsets associated with the transitions from the current state $W1_nW2_nW3_nW4_nW5_nW6_n$ to the three next states $W5_nW6_nX5X6X3X4$, where $X5$ and $X6$ are binary variables and $X5X6$ is not equal to $X1X2$, all belong to the same 4D subfamily (see Table III). Furthermore, if Y is the 4D subset associated with the transition from a current state $W1_nW2_nW3_nW4_nW5_nW6_n$ to an even-numbered (or odd-numbered) next state, then for each of the four values of a bit pair $X1X2$, Y is also the 4D subset associated with the transition from the current state $W1_nW2_nX1X2W5_nW6_n$ to an odd-numbered (or even-numbered) next state.

$I1_{n+1}I2_{n+1}I3_{n+1}$	$Z2_nZ3_nZ4_n$	$Z2_{n+1}Z3_{n+1}Z4_{n+1}$	$Z2_{n+2}Z3_{n+2}Z4_{n+2}$	$Z2_{n+3}Z3_{n+3}Z4_{n+3}$
0 X X	0 $I2_{n+1}I3_{n+1}$	0 $I4_{n+1}I5_{n+1}$	0 $I6_{n+1}I7_{n+1}$	0 $I1_{n+2}I2_{n+2}$
1 0 0	1 0 0	0 $I4_{n+1}I5_{n+1}$	0 $I6_{n+1}I7_{n+1}$	0 $I1_{n+2}I2_{n+2}$
1 0 1	0 $I4_{n+1}I5_{n+1}$	1 0 0	0 $I6_{n+1}I7_{n+1}$	0 $I1_{n+2}I2_{n+2}$
1 1 0	0 $I4_{n+1}I5_{n+1}$	0 $I6_{n+1}I7_{n+1}$	1 0 0	0 $I1_{n+2}I2_{n+2}$
1 1 1	0 $I4_{n+1}I5_{n+1}$	0 $I6_{n+1}I7_{n+1}$	0 $I1_{n+2}I2_{n+2}$	1 0 0

Fig. 10. 8D block encoder.

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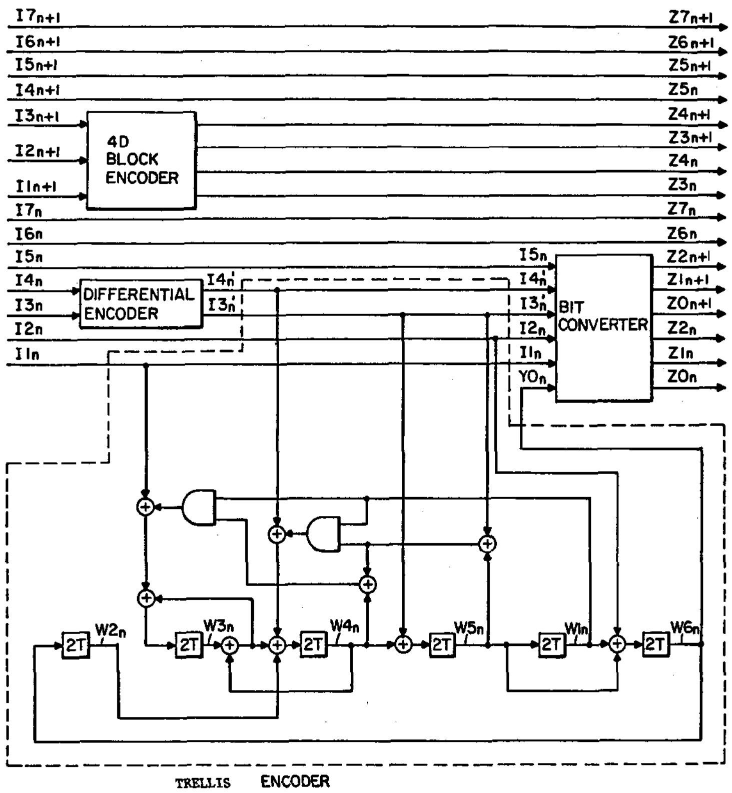

Fig. 11. 64-state code with 4D rectangular constellation.

The above statements together guarantee that the MSED of the code is at least $5d_0^2$. Since there exists an error event with a squared Euclidean distance $5d_0^2$, the coding gain of this code over the uncoded 128-CR is 5.63 dB. This coding gain may be segregated into two parts, a gain of 6.99 dB from the trellis code if the 4D constellation were not expanded from 2^{14} to 2^{15} points, and a loss of 1.36 dB due to that expansion. With some straightforward calculation, the error coefficient of the code may be shown to be 144 per 4D point, equivalent to 72 per 2D point.

Since the 4D subsets are not invariant under any of the rotations corresponding to the three phase ambiguities of the constellation, three one-to-one functions $F1$, $F2$, and $F3$, which map each state of the trellis encoder into another state and correspond to 90°, 180°, and 270° rotations, respectively, are needed as required by the second general principle of Section IV-A. Those three functions are defined as follows:

$$F1: W1_pW2_pW3_pW4_pW5_pW6_p \to \overline{W1_p}W2_pX3W4_pX5W6_p$$

$$F2: W1_pW2_pW3_pW4_pW5_pW6_p \to W1_pW2_p\overline{W3_p}W4_pW5_pW6_p$$

$$F3: W1_pW2_pW3_pW4_pW5_pW6_p \to \overline{W1_p}W2_pY3W4_pY5W6_p$$

where

$$X3X5 = (W3_pW5_p + 01)\,\mathrm{mod}_{\mathrm{base}\,2}$$

and

$$Y3Y5 = (W3_pW5_p + 11)\,\mathrm{mod}_{\mathrm{base}\,2}.$$

The differential encoder of Fig. 11 is the same as that of Fig. 6 except that its input and output bit pairs are now named as $I4_nI3_n$ and $I4'_nI3'_n$ rather than $I3_nI2_n$ and $I3'_nI2'_n$, respectively.

D. Extensions

The number of states of the 16-state 4D code of Section IV-A or 64-state 8D code of Section IV-B may be reduced without sacrificing the coding gain, but the error coefficient is increased. For example, a 32-state code with the same partitioning of the 8D rectangular constellation as in Section IV-B can provide 5.41 dB coding gain, the same as the 64-state code of that subsection, but its error coefficient is 124 per 2D point, compared to 60 for the 64-state code. The smallest number of states required for a code with the partitioning of the 4D rectangular constellation of Section IV-A to provide 4.66 dB coding gain is eight, the same as the number of 4D subsets of that partitioning. The smallest number of states required for a code with the partitioning of the 8D rectangular constellation of Section IV-B to provide 5.41 dB coding gain is 16, again the same as the number of 8D subsets of the partitioning.

Given the partitioning of the 4D or 8D rectangular constellation of Section IV-A or -B, it is impossible to increase the coding gain further or reduce the error coefficient of the 16-state or 64-state code of those two subsections. With a finer partitioning of the 4D or 8D rectangular constellation based on the same partitioning of the constituent 2D constellations, however, it becomes possible to reduce the error coefficient further by increasing the

number of states. For example, a 32-state code with the 4D rectangular constellation partitioned into 16 subsets, each subset corresponding to a 4D type of Table I, can provide 4.66 dB coding gain, the same as that of the 16-state code of Section IV-A, but the error coefficient is four per 2D point, less than the 12 of the 16-state code and the same as that for the uncoded 128-CR. Note that this kind of partitioning of a multidimensional lattice may be easily derived from a coarser partitioning of the same lattice obtained by following the principles described in Section II.

To increase further the coding gain of the 16-state or 64-state code of Sections IV-A or -B, a finer partitioning of the 4D or 8D constellation based on a finer partitioning of the constituent 2D constellations should be used. The 64-state code of Section IV-C is an example. Note that the number of states of that code cannot be reduced without sacrificing the coding gain. On the other hand, the coding gain can be further increased, or the error coefficient reduced, using the same partitioning of the 4D rectangular constellation as in Section IV-C, if the number of states is increased beyond 64. The upper limit on the coding gain in this case is 7.67 dB, and the lower limit on the error coefficient in the case of 7.67 dB coding gain is 12 per 2D point.

With a 16D rectangular constellation of 2^{57} points constructed from a 144-point 2D constellation and partitioned into 32 subsets as in the previous sections, it can be shown that a 32-state code can be constructed to achieve a MSED of $4d_0^2$. The coding gain of this code over the uncoded 128-CR is 5.74 dB. This is also the largest possible coding gain that can be achieved with the 32-subset partitioning of the 16D rectangular constellation. This coding gain may be segregated into two parts, a gain of 6.02 dB from the trellis code if the 16D constellation were not expanded from 2^{56} to 2^{57} points, and a loss of 0.28 dB due to that expansion. This expansion loss is only 0.33 dB less than that for the 8D code of Section IV-B. The error coefficient of this code is larger than 1000 per 2D point. This number can be reduced to 412 if the number of states is increased to 128. The lower limit on the error coefficient using the 32-subset partitioning of the 16D constellation is 284 per 2D point, which is 1/8 the number (2272) of nearest neighbors to any point in the same 16D subset.

Trellis codes using an 8D constellation E_8 of 2^{29} points constructed from a 320-point 2D constellation and partitioned into 16 subsets as in the previous sections are described next. Although the partitioning of E_8 is such that there is no 8D family in between the constellation and the 8D subsets (see Fig. 5), we group the 16 8D subsets into two equal-sized 8D families in an arbitrary manner. The intrafamily MSED is therefore the same as the MSED of the constellation. Now note that the distance relationship between an 8D family and its eight subsets of the constellation E_8 is identical to that between an 8D family and its eight subsets of the 8D rectangular constellation partitioned in accordance with Table II. Since the construction of a trellis code with that partitioning of the 8D rectangular constellation does not depend on the interfamily MSED, all the trellis codes constructed for the 8D rectangular constellation can be used for the constellation E_8.

In particular, the rate-3/4, 64-state code of Section IV-B can be used with E_8 to achieve a MSED of $8d_0^2$, which is the MSED of each 8D subset. Since the average power of the constellation E_8 is $47.133d_0^2$, the coding gain of this code over the uncoded 128-CR is 5.41 dB. This is also the largest possible coding gain that can be achieved with the 16-subset partitioning of E_8. This coding gain may be segregated into three parts: a gain of 3.04 dB from the use of E_8 [3], another gain of 3.01 dB from the trellis code if the constellation E_8 were not expanded from 2^{28} to 2^{29} points, and a loss of 0.64 dB due to that expansion. The error coefficient of this code is the minimum, 240 per 8D point (or 60 per 2D point), which is the number of nearest neighbors to any point in the same 8D subset (an E_8 lattice). Note that both the coding gain and error coefficient of this code are the same as those of the 64-state code with the 8D rectangular constellation of Section IV-B.

The fact that the large MSED of E_8 does not help a trellis code achieve additional coding gain suggests the consideration of the 8D lattice DE_8. The MSED of the lattice DE_8 is only $2d_0^2$. An 8D constellation DE_8 of 2^{29} points can be constructed from a 256-point 2D constellation with an average power $40.6875d_0^2$, as shown in Section III. Both the size of the constituent 2D constellation and the average power of the constellation DE_8 are less than those of an 8D constellation E_8 of equal size. The constellation DE_8 is partitioned into two families of 16 subsets each as in Section II. The intrafamily and intrasubset MSED's are $4d_0^2$ and $8d_0^2$, respectively, which are the same as those of the partitioning of E_8 described above. A rate-4/5, 32-state code can be constructed with the constellation DE_8 to achieve an MSED of $8d_0^2$. The coding gain of this code over the uncoded 128-CR is therefore 6.05 dB. This is also the largest possible coding gain that can be achieved with the 32 subsets of the constellation DE_8. With some calculation, this coding gain may be segregated into three parts: a gain of 0.93 dB from the use of DE_8, another gain of 6.02 dB from the trellis code if the constellation DE_8 were not expanded from 2^{28} to 2^{29} points, and a loss of 0.9 dB due to that expansion. Comparing this segregation of coding gain with that for the constellation E_8, one can see that although the lattice DE_8 is a poor lattice for block-coded modulation, it is a good lattice for trellis-coded modulation. The error coefficient of this code is more than 500 per 2D point. This number can be reduced to 316 and 124 if the number of states is increased to 64 and 128, respectively. Further improvement is certainly possible by further increasing the number of states.

A recent report [16] gives trellis-coded modulation schemes based on a partitioning of the 4D lattice D_4, the most complex using a 64-state trellis code. Similar schemes may be constructed using the techniques of this paper, with a 4D constellation D_4 of 2^{15} points constructed from

a 256-point 2D constellation and partitioned into sixteen subsets as in the previous sections. A 64-state code can be shown to achieve a coding gain of 6.05 dB over the uncoded 128-CR. This is also the largest possible coding gain that can be achieved with the 16-subset partitioning of the constellation D_4. The coding gain may be segregated into three parts: a gain of 1.64 dB from the use of D_4 [3], another gain of 6.02 dB from the trellis code if the constellation D_4 were not expanded from 2^{14} to 2^{15} points, and a loss of 1.61 dB due to that expansion. The error coefficient of this code is, however, quite large, about ten times as large as that of the 64-state code with the 4D rectangular constellation of Section IV-C. It may be interesting to note here that the 4D rectangular lattice may be characterized as the union of D_4 and a rotated version of D_4 (see Fig. 4), which is similar to the relationship between the lattices DE_8 and E_8 and is another motivation for us to consider the lattice DE_8.

V. Decoder

A conventional maximum-likelihood decoding algorithm such as the Viterbi algorithm is used as the decoder [17]. As a preliminary step, the decoder must determine the point in each of the multidimensional subsets which is closest to the received point, and calculate its associated metric (the squared Euclidean distance between the two points). Because of the way in which a multidimensional constellation is partitioned, the closest point in each multidimensional subset and its associated metric may be obtained as follows. Each received $2N$-dimensional point is divided into a pair of N-dimensional points. The closest point in each $2N$-dimensional subset and its associated metric are found based on the point in each of the N-dimensional subsets which is closest to the corresponding received N-dimensional point and its associated metric. The N-dimensional subsets are those subsets which are used in Section II to construct the $2N$-dimensional subsets. The foregoing process may be used iteratively to obtain the closest point in each $2N$-dimensional subset and its associated metric based on the closest point in each of the basic 2D subsets and its associated metric.

As an example, we show how to determine the closest point in each of the 16 subsets of the 8D rectangular constellation of Section IV-B and its associated metric (see Fig. 12). First, for each of the four received 2D points of a received 8D point, the decoder determines the closest 2D point in each of the four 2D subsets of the 160-point 2D constellation of Fig. 2, and calculates its associated metric. These metrics are called 2D subset metrics. Because there are only 40 2D points in each of the four 2D subsets, this step is quite easy, being no more complex than that required for a 2D code.

Next, the decoder determines the 4D point in each of the 16 4D types (see Table I) which is closest to the first received 4D point (the 4D point corresponding to the first and second 2D points of the received 8D point), and calculates its associated metric. These metrics are called 4D type metrics. The 4D type metric for a 4D type is

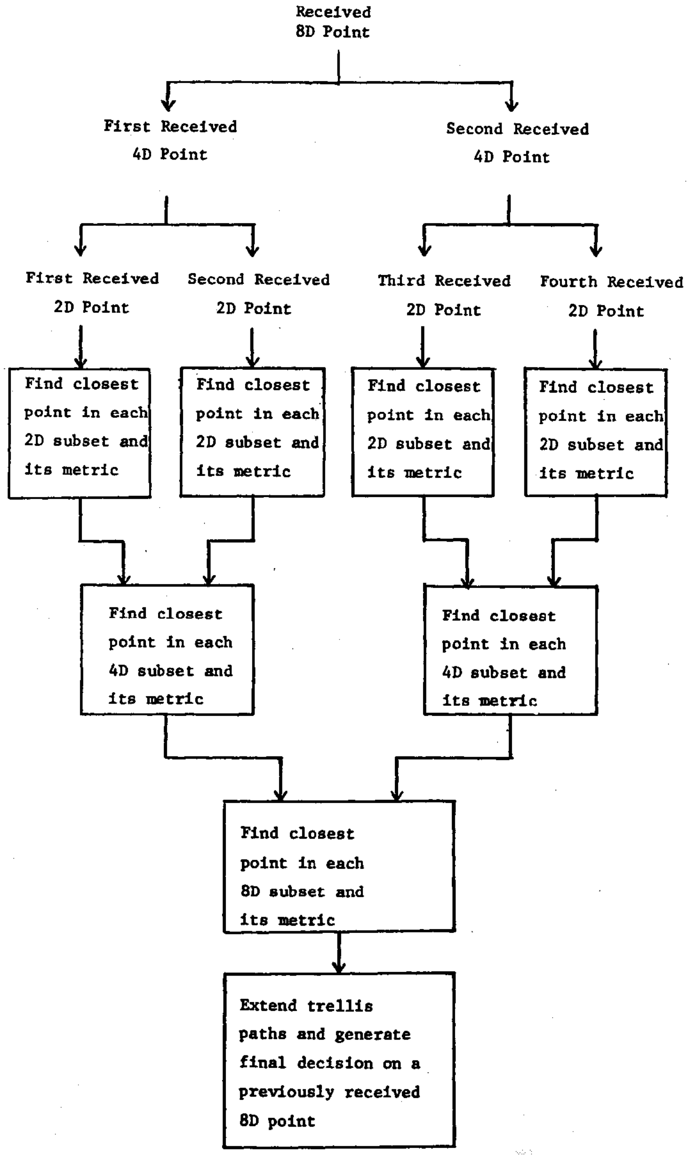

Fig. 12. Viterbi decoding algorithm for 64-state code of Fig. 8.

obtained merely by adding the two 2D subset metrics for the pair of 2D subsets corresponding to that 4D type. The decoder then compares the two 4D type metrics for the pair of 4D types within each 4D subset (see Table I). The smaller 4D type metric becomes the 4D subset metric associated with that 4D subset, and the 4D point associated with the smaller 4D type metric is the 4D point in that 4D subset which is closest to the first received 4D point. The same process is repeated for the second received 4D point.

The decoder then determines the closest 8D point in each of the 64 8D types (see Table II) and calculates its associated metric. These metrics are called 8D type metrics. The 8D type metric for an 8D type is obtained by adding the two 4D subset metrics for the pair of 4D subsets corresponding to that 8D type. Finally, the decoder compares the four 8D type metrics corresponding to the four 8D types within each 8D subset (see Table II). The smallest 8D type metric becomes the 8D subset metric

associated with that 8D subset, and the 8D point associated with the smallest 8D type metric is the closest 8D point in that 8D subset. These 8D subset metrics are then used to extend the trellis paths and generate final decisions on the transmitted 8D points in the usual way.

The final decision on a transmitted 8D point obtained from the foregoing procedure may not be a valid point of the 8D constellation of Section IV-B because more than one of the four 2D points of the decision may come from the outer group of the 2D constellation of Fig. 2. When this happens, a modification must be made in the procedure to arrive at a valid 8D point. This type of error is caused by the boundary effect of the finite constellation. Since we did not consider that effect in our calculation of the error coefficient in the last section, this type of error is already included in the error coefficient.

Because of the construction of multidimensional constellations described in Section III, at the receiver the mapping from each decoded multidimensional point back to the information bits is simplified. Again, we will use the code of Section IV-B to illustrate this inverse mapping procedure. Each of the four 2D points corresponding to the final decision on a transmitted 8D point is first mapped back to eight Z bits (see Fig. 2 and Table IV). Then performing the inverse conversions corresponding to the bit converter and 8D block encoder (see Figs. 9 and 10) followed by a differential decoding operation produces the desired 28 information bits. The mapping from a 2D point back to the eight Z bits requires a table of only 160×8 bits. The inverse conversion corresponding to the bit converter requires a table of only 256×7 bits. The inverse conversion corresponding to the 8D block encoder may be done with a short procedure which does not even require a table.

VI. Comparisons and Conclusion

To compare trellis codes using various partitionings of multidimensional or 2D constellations, a way to measure code complexity is needed. With the simplified multidimensional constellation mapping as described in Section IV and the simplified decoding method as described in Section V, a good measure of code complexity is the ratio of the total number of allowed state transitions of a code to the number of signaling intervals corresponding to the dimensionality of its constellation. For example, for the eight-state 2D code used in the CCITT standards V.32 and V.33, this ratio is 32 [2], [4], [5]. For the 16-state 4D code of Section IV-A, this ratio is also 32.

The reason for using this ratio to measure code complexity is that to update the path metric of each state of a code in the Viterbi decoding algorithm, the path metrics associated with all the transitions leading to that state need to be calculated and compared. This must be done only once every block of N signaling intervals, where $2N$ is the number of dimensions in the constellation. The updating of the path metrics dominates the code complexity. (The last statement is valid at least for the codes to be compared in Table VI. A refined measure of code complexity, which takes into account the calculation used to obtain multidimensional subset metrics, may be considered for codes with a small number of states relative to their number of dimensions.)

Table VI lists the characteristics of some of the multidimensional trellis codes that have been studied, along with the characteristics of some 2D trellis codes from [1], [2]. (Some of the 2D code characteristics have not been published previously.) The error coefficients for the 64- and 128-state 2D codes are due to [18]. The codes in Table VI are listed by increasing complexity and, for codes of equal complexity, by increasing number of dimensions. Although some characteristics shown in Table VI are for the case where the number of information bits transmitted per 2D signaling interval is equal to seven, the conclusions drawn below may be generally applied to other transmission rates.

The principal conclusion is that for the same (modest) complexity (i.e., complexity less than or equal to that of the 32-state 2D code), trellis-coded modulation with multi-

TABLE VI
Code Comparison

Scheme	Lattice	Number of Points in Constituent 2D Constellation[a]	Number of States of Trellis Code	Number of Multi-Dimensional Subsets	Relative Code Complexity	Coding Gain[a,b] (dB)	Error Coefficient (per 2D Point)	Peak-to-Average Power Ratio[a]
1	2D Rectangular	256	8	8	1	4.01	16	1.93
2	4D Rectangular	192	16	8	1	4.66	12	2.16
3	2D Rectangular	256	32	8	4	4.80	16	1.93
4	8D Rectangular	160	64	16	4	5.41	60	2.14
5	E_8	320	64	16	4	5.41	60	2.17
6	2D Rectangular	256	64	8	8	5.47	56	1.93
7	D_4	256	64	16	8	6.05	828	1.93
8	DE_8	256	64	32	8	6.05	316	1.93
9	16D Rectangular	144	128	32	8	5.74	412	2.03
10	2D Rectangular	256	128	8	16	6.05	344	1.93
11	4D Rectangular	192	64	32	16	5.63	72	2.16
12	DE_8	256	128	32	16	6.05	124	1.93

[a] For transmitting seven information bits per 2D signaling interval.
[b] As compared to the uncoded 128-CR.

dimensional rectangular constellations is superior to using 2D constellations. Using a multidimensional rectangular constellation not only improves the performance in terms of both the coding gain and error coefficient, but also reduces the size of the constituent 2D constellations. A smaller 2D constellation implies better performance when the received signal contains signal-dependent noise. Examples of this conclusion are Scheme 1 versus Scheme 2 and Scheme 3 versus Scheme 4 of Table VI. The better performance of Schemes 2 and 4 is not obtained at the cost of increasing the peak-to-average power ratio of the constellations to an unacceptably large value. This is also true for all other multidimensional trellis codes appearing in this paper. It is important to keep this ratio small because the transmission medium may distort the transmitted signal nonlinearly.

Trellis codes with the densest 8D constellation E_8 do not seem to have any advantage over codes using the 8D rectangular constellation. There is, however, a disadvantage associated with the constellation E_8, namely that the constituent 2D constellation of E_8 is twice as large as that for the 8D rectangular constellation, as may be seen by comparing Schemes 4 and 5.

Using a rectangular constellation with more than eight dimensions seems to yield diminishing returns, as may be seen by comparing Scheme 4 and 9. The size of the constituent 2D constellations of Scheme 9 is 9/10 times that of Scheme 4, which is not much smaller. The coding gain of Scheme 9 is only 0.33 dB more than that of Scheme 4, but the error coefficient of Scheme 9 is about seven times that of Scheme 4. Even worse, the complexity of Scheme 9 is twice as much as that of Scheme 4.

For higher complexity, using a multidimensional rectangular constellation has less to offer. Schemes 10 and 11 have about the same performance, comparing both the coding gain and error coefficient. The advantage of a smaller constituent 2D constellation for the multidimensional rectangular constellation is, however, preserved.

The advantage of a smaller constituent 2D constellation for the multidimensional constellation disappears when the densest 4D constellation D_4 or the 8D constellation DE_8 is used. Trellis codes with the constellation DE_8 are only slightly better than their 2D correspondents, as may be seen by comparing Schemes 6 and 8, or Schemes 10 and 12. DE_8 shows, however, an important concept. That is, while it is desirable that the multidimensional subsets used in trellis-coded modulation be dense lattices, it is not necessarily desirable that the overall multidimensional constellation be as dense. Multidimensional rectangular constellations are the extreme case of the above statement. We have not found that trellis codes using the densest 4D constellation D_4 have any advantage.

From another viewpoint, using a multidimensional constellation instead of a 2D constellation with a trellis code reduces the code complexity while maintaining the same performance in terms of both the coding gain and error coefficient. Examples of this conclusion are Scheme 2 versus Scheme 3, Scheme 4 versus Scheme 6, and Scheme 8 versus Scheme 10.

Generally speaking, it is easier to construct a trellis code that is transparent to all phase ambiguities of the constellation using a multidimensional instead of a 2D constellation. The reason is that some or all of the phase ambiguities of a multidimensional constellation may be removed by a careful partitioning of the multidimensional constellation into subsets as described in Section II, without the involvement of the trellis code. Examples are Schemes 2, 4, 5, 8, 9, and 12. Scheme 11 is also transparent to all phase ambiguities of its constellation as demonstrated in Section IV-C. All phase ambiguities of Scheme 11 are, however, removed with the involvement of the trellis code.

These multidimensional trellis codes may be generalized to rectangular constellations with dimensions other than 4, 8, or 16, to other multidimensional constellations with rectangular or nonrectangular constituent 2D constellations, and to trellis codes of rate other than $m/m+1$.

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EXHIBIT D

United States Patent [19]

Wei

[11] **Patent Number: 4,641,327**

[45] **Date of Patent: Feb. 3, 1987**

[54] **FRAME SYNCHRONIZATION IN TRELLIS-CODED COMMUNICATION SYSTEMS**

[75] Inventor: **Lee-Fang Wei**, Westwood, Mass.

[73] Assignee: **Codex Corporation**, Mansfield, Mass.

[21] Appl. No.: **753,182**

[22] Filed: **Jul. 9, 1985**

[51] **Int. Cl.**[4] **H04L 7/04**; G06F 11/10

[52] **U.S. Cl.** **375/114**; 371/43; 375/38

[58] **Field of Search** 375/13, 34, 38, 39, 375/58, 114, 115, 116, 25, 106; 370/105–107; 371/40, 43, 42, 44, 46; 178/22.04, 22.05

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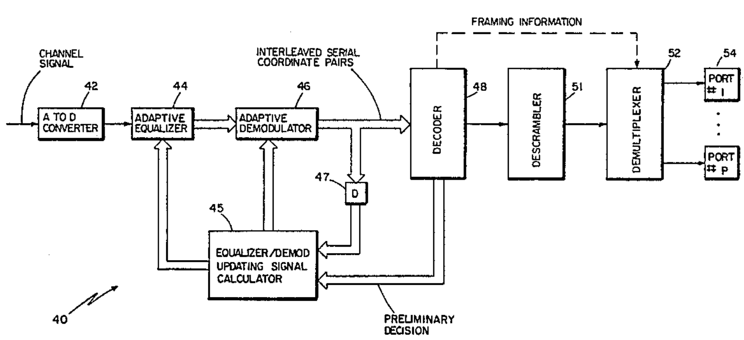
Primary Examiner—Robert L. Griffin

Assistant Examiner—M. Huseman

[57] **ABSTRACT**

Frame synchronization is accomplished in a trellis-coded communication system by causing the sequence of signal points that results when the receiver incorrectly determines the start of each frame to be an impermissible sequence, and detecting the existence of the impermissible sequence by monitoring the rate of occurrence of non-zero difference between the minimum branch metric and the minimum path metric of a maximum likelihood decoding algorithm, such as the Viterbi decoding algorithm. In another aspect, an interleaver and a deinterleaver are used to assure that impermissible sequences result when frame synchronization is lost.

13 Claims, 7 Drawing Figures



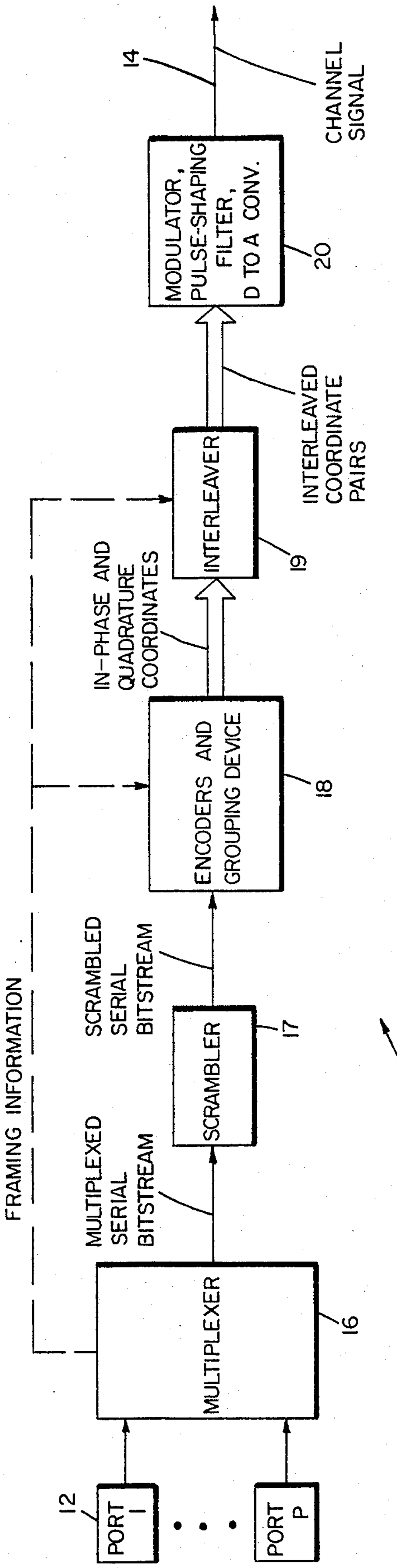

PORT 1
PORT P
12
MULTIPLEXER
16
MULTIPLEXED SERIAL BITSTREAM
SCRAMBLER
17
SCRAMBLED SERIAL BITSTREAM
ENCODERS AND GROUPING DEVICE
18
IN-PHASE AND QUADRATURE COORDINATES
INTERLEAVER
19
INTERLEAVED COORDINATE PAIRS
MODULATOR, PULSE-SHAPING FILTER, D TO A CONV.
20
CHANNEL SIGNAL
14
FRAMING INFORMATION
10

FIG 1

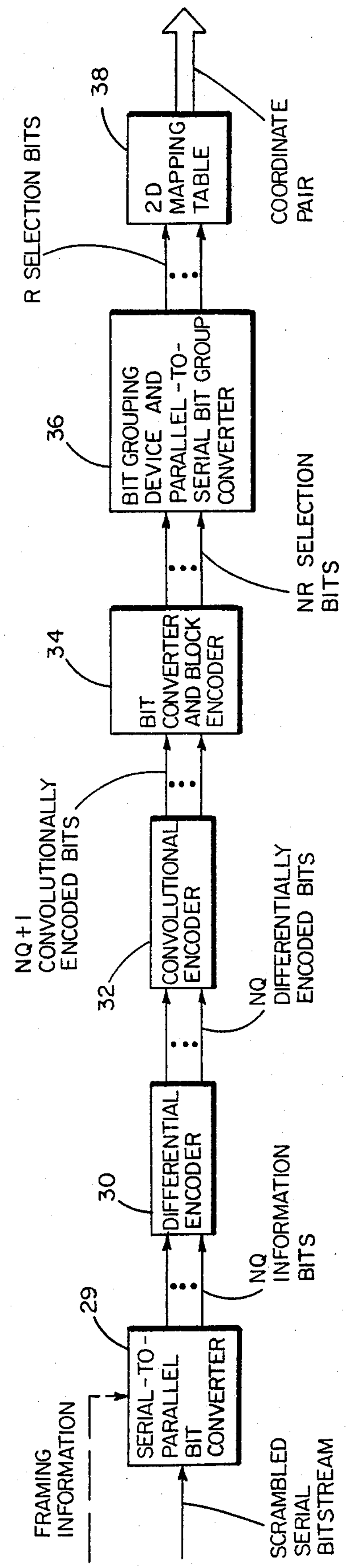

FRAMING INFORMATION
SCRAMBLED SERIAL BITSTREAM
SERIAL-TO-PARALLEL BIT CONVERTER
29
NQ INFORMATION BITS
DIFFERENTIAL ENCODER
30
NQ DIFFERENTIALLY ENCODED BITS
CONVOLUTIONAL ENCODER
32
NQ+1 CONVOLUTIONALLY ENCODED BITS
BIT CONVERTER AND BLOCK ENCODER
34
NR SELECTION BITS
BIT GROUPING DEVICE AND PARALLEL-TO-SERIAL BIT GROUP CONVERTER
36
R SELECTION BITS
2D MAPPING TABLE
38
COORDINATE PAIR
18

FIG 2

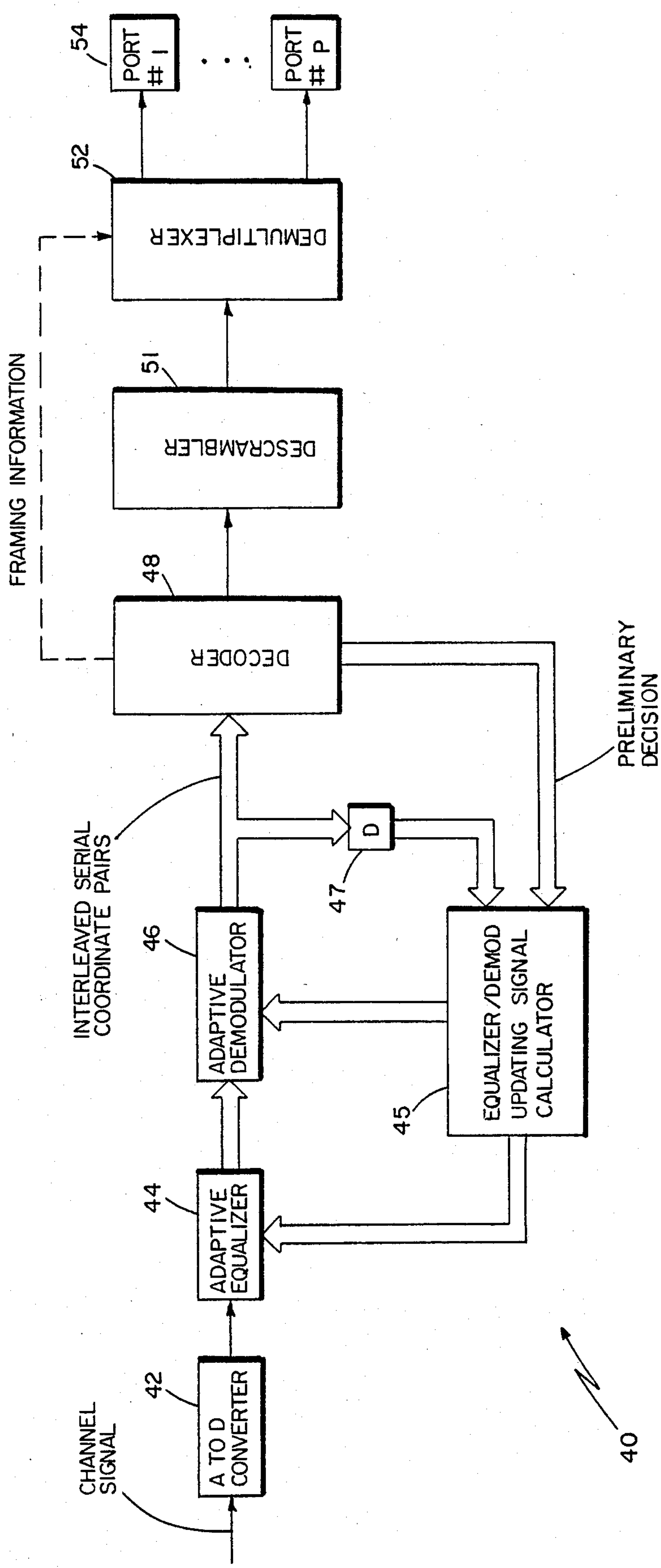

CHANNEL SIGNAL
A TO D CONVERTER
42
ADAPTIVE EQUALIZER
44
ADAPTIVE DEMODULATOR
46
EQUALIZER/DEMOD UPDATING SIGNAL CALCULATOR
45
INTERLEAVED SERIAL COORDINATE PAIRS
D
47
PRELIMINARY DECISION
DECODER
48
DESCRAMBLER
51
DEMULTIPLEXER
52
FRAMING INFORMATION
PORT # 1
54
PORT # P
40

FIG 3

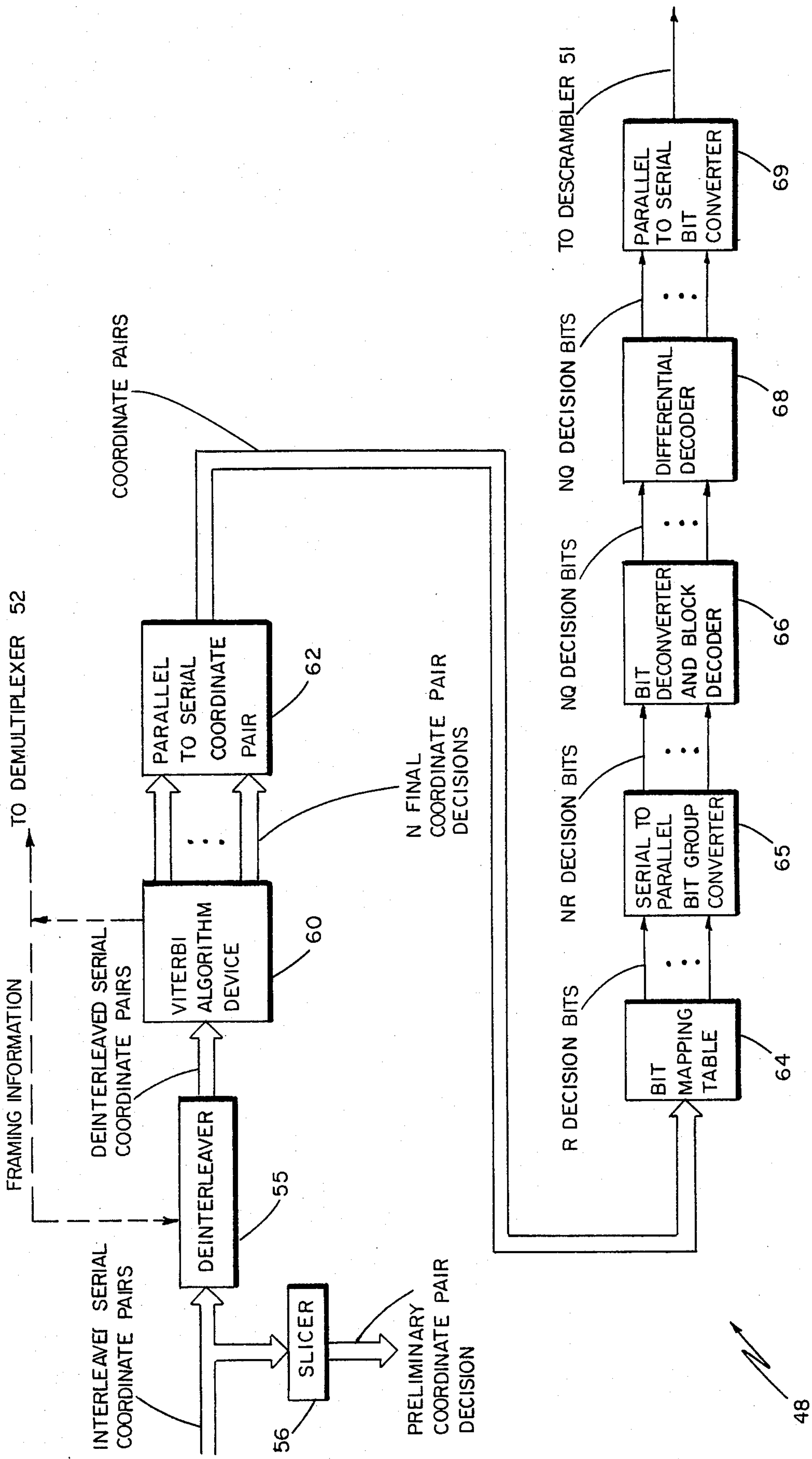
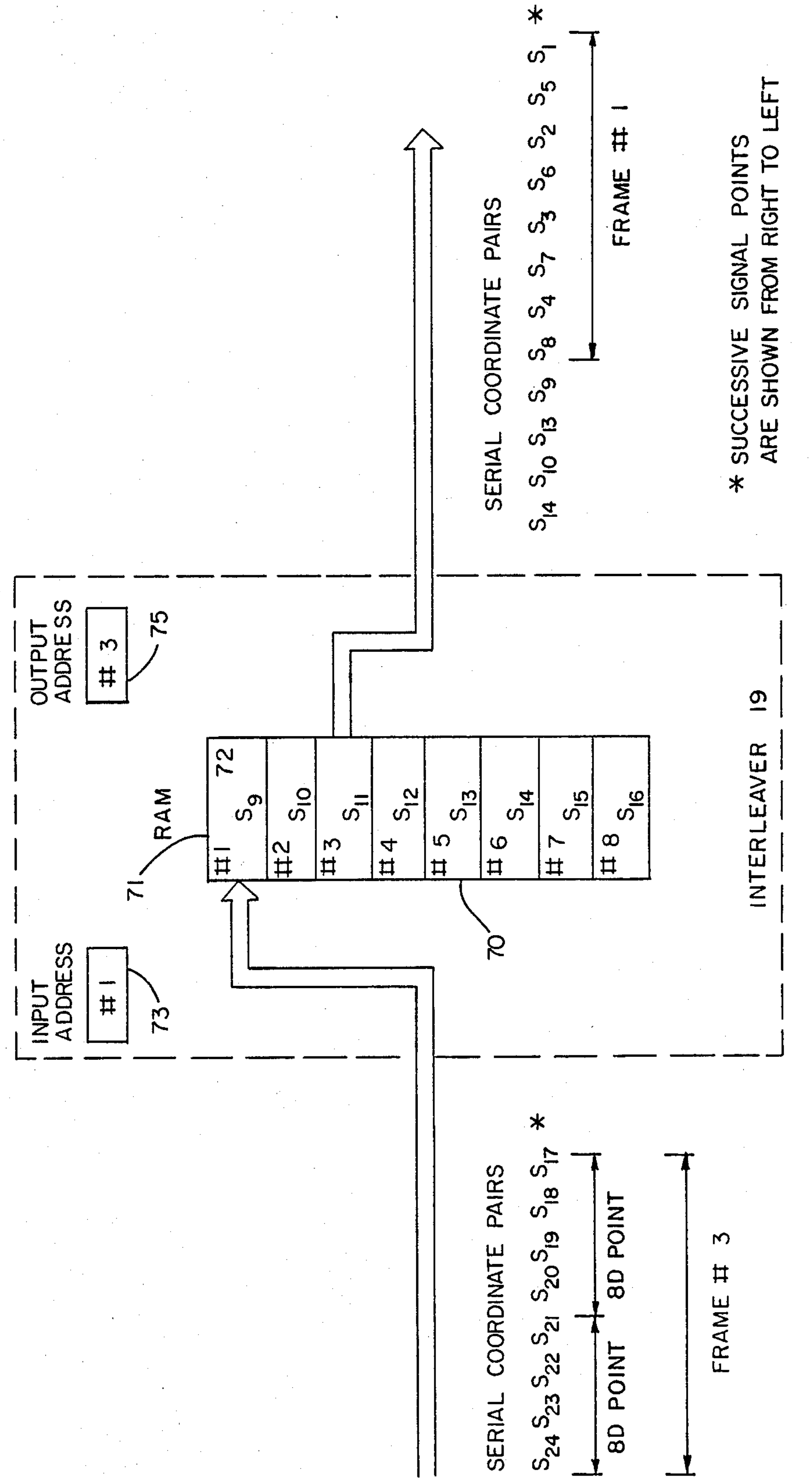
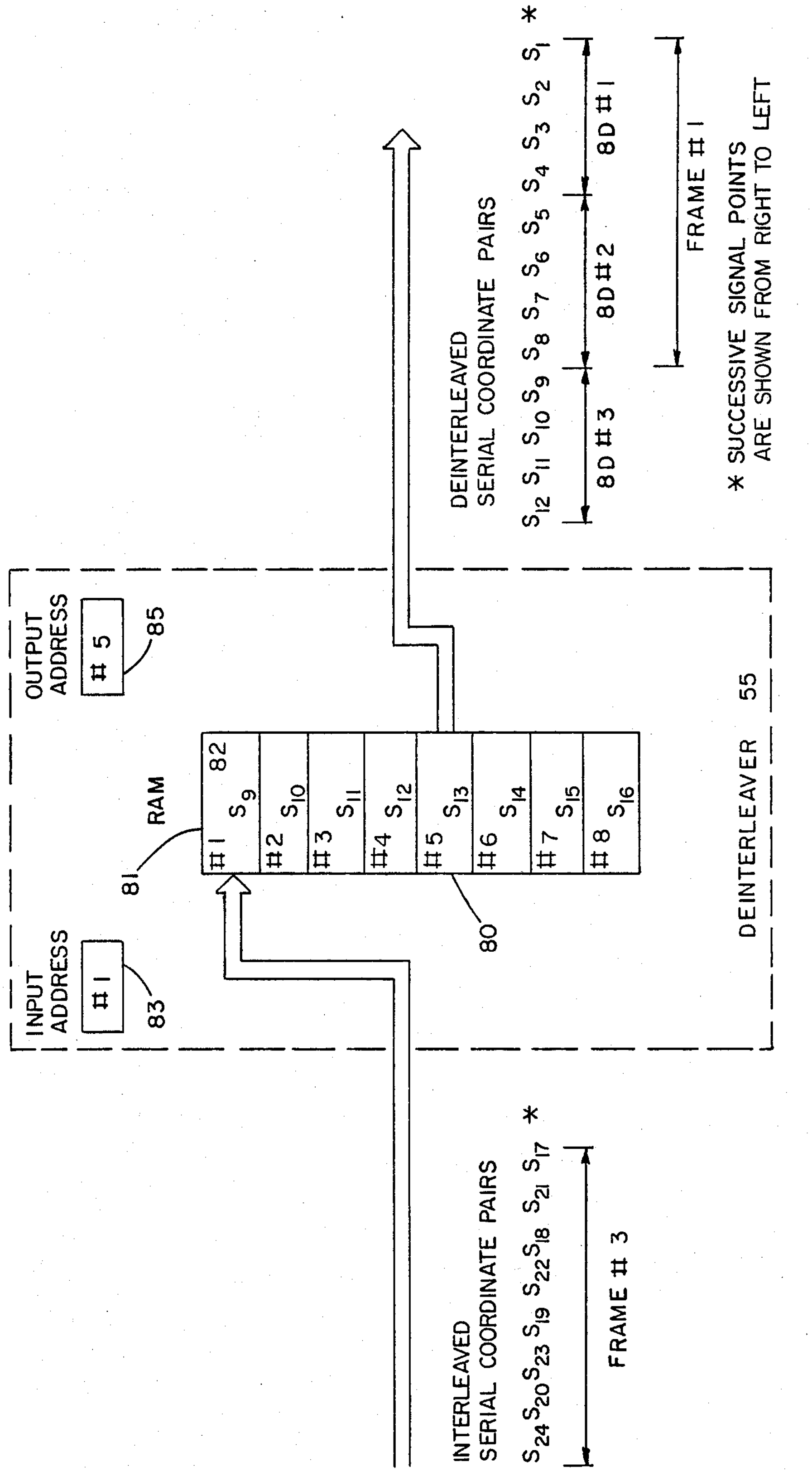

INTERLEAVED SERIAL COORDINATE PAIRS
56
SLICER
PRELIMINARY COORDINATE PAIR DECISION
DEINTERLEAVER
55
FRAMING INFORMATION
TO DEMULTIPLEXER 52
DEINTERLEAVED SERIAL COORDINATE PAIRS
VITERBI ALGORITHM DEVICE
60
N FINAL COORDINATE PAIR DECISIONS
PARALLEL TO SERIAL COORDINATE PAIR
62
COORDINATE PAIRS
R DECISION BITS
BIT MAPPING TABLE
64
NR DECISION BITS
SERIAL TO PARALLEL BIT GROUP CONVERTER
65
NQ DECISION BITS
BIT DECONVERTER AND BLOCK DECODER
66
NQ DECISION BITS
DIFFERENTIAL DECODER
68
TO DESCRAMBLER 51
PARALLEL TO SERIAL BIT CONVERTER
69
48

FIG 4



SERIAL COORDINATE PAIRS
S14 S10 S13 S9 S8 S4 S7 S3 S6 S2 S5 S1 *
FRAME # 1
* SUCCESSIVE SIGNAL POINTS ARE SHOWN FROM RIGHT TO LEFT
OUTPUT ADDRESS
3
75
INPUT ADDRESS
1
73
RAM
71
72
#1 S9
#2 S10
#3 S11
#4 S12
#5 S13
#6 S14
#7 S15
#8 S16
70
INTERLEAVER 19
SERIAL COORDINATE PAIRS
S24 S23 S22 S21 S20 S19 S18 S17 *
8D POINT
8D POINT
FRAME # 3

FIG 5



INTERLEAVED SERIAL COORDINATE PAIRS
$S_{24} S_{20} S_{23} S_{19} S_{22} S_{18} S_{21} S_{17}$ *
FRAME # 3
INPUT ADDRESS
1
83
81
RAM
82
#1 S_9
#2 S_{10}
#3 S_{11}
#4 S_{12}
#5 S_{13}
#6 S_{14}
#7 S_{15}
#8 S_{16}
80
OUTPUT ADDRESS
5
85
DEINTERLEAVER 55
DEINTERLEAVED SERIAL COORDINATE PAIRS
$S_{12} S_{11} S_{10} S_9 S_8 S_7 S_6 S_5 S_4 S_3 S_2 S_1$ *
8D # 3
8D # 2
8D # 1
FRAME # 1
* SUCCESSIVE SIGNAL POINTS ARE SHOWN FROM RIGHT TO LEFT

FIG 6

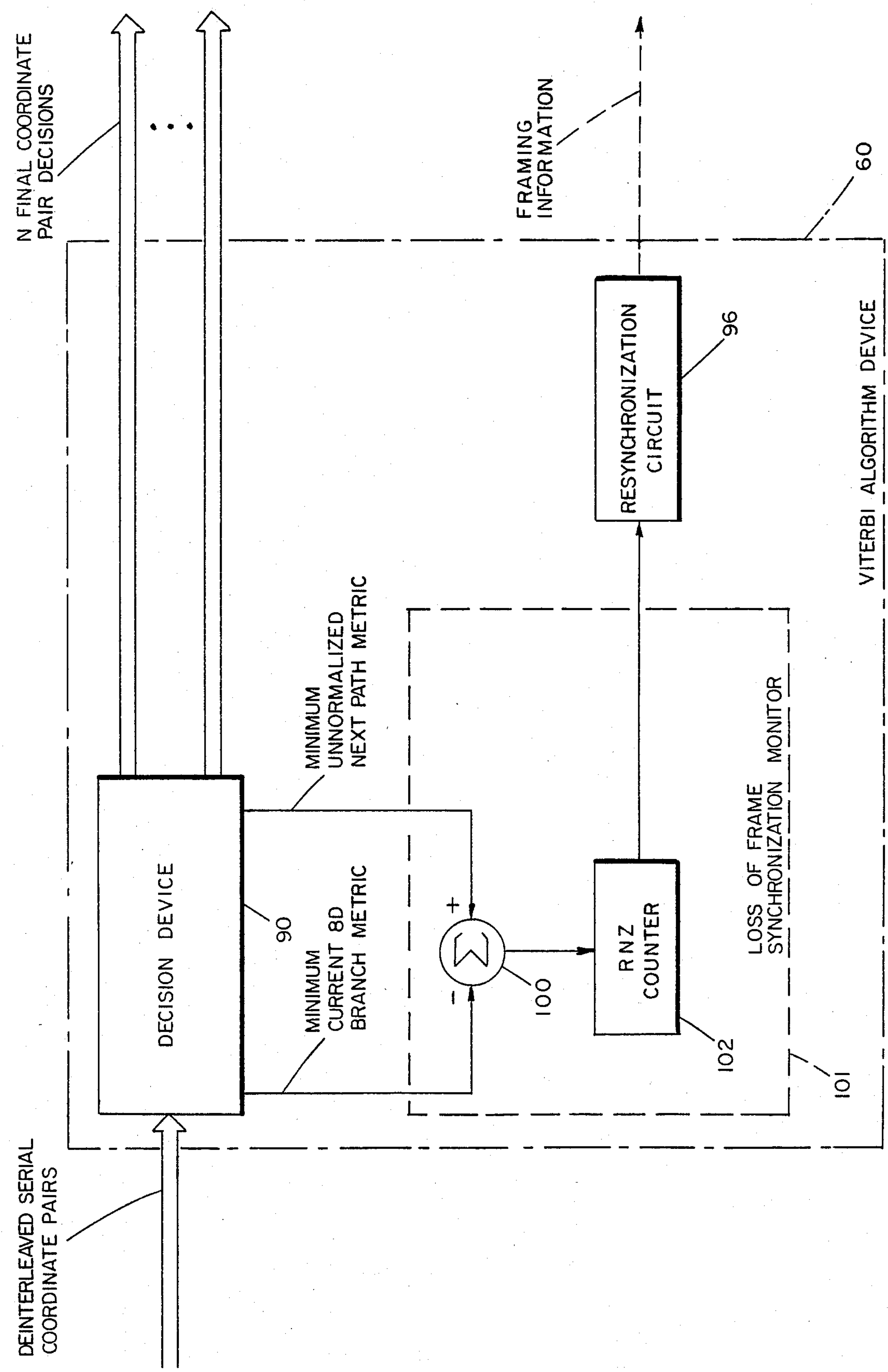

N FINAL COORDINATE PAIR DECISIONS
FRAMING INFORMATION
60
RESYNCHRONIZATION CIRCUIT
96
VITERBI ALGORITHM DEVICE
MINIMUM UNNORMALIZED NEXT PATH METRIC
DECISION DEVICE
90
MINIMUM CURRENT 8D BRANCH METRIC
+
−
100
RNZ COUNTER
102
LOSS OF FRAME SYNCHRONIZATION MONITOR
101
DEINTERLEAVED SERIAL COORDINATE PAIRS

FIG 7

FRAME SYNCHRONIZATION IN TRELLIS-CODED COMMUNICATION SYSTEMS

BACKGROUND OF THE INVENTION

This invention relates to maintaining frame synchronization between the receiver and the transmitter in a trellis-coded communication system.

In some trellis-coded communication systems the two-dimensional signal points sent by the transmitter are grouped into frames, and the receiver must be able to identify (i.e. synchronize itself to) the beginning of each frame for proper operation.

In so-called multi-dimensional trellis-coded systems (for example systems of the kind disclosed in Wei, U.S. patent application Ser. No. 727,398, filed Apr. 25, 1985, assigned to the same assignee as this invention, and incorporated herein by reference) the two-dimensional signal points carried on the channel between the transmitter and receiver are organized as multi-dimensional signal points, each multi-dimensional signal point comprising more than one two-dimensional signal point. At the receiver, in order to decode the multi-dimensional signal points, the receiver must be synchronized to identify the first two-dimensional signal point of each multi-dimensional signal point.

In so-called multiplexed communication systems, a high-bit-rate stream of bits to be transmitted is segmented into multiplexing frames. Each frame is built up (multiplexed) based on bits delivered from several ports each serving a relatively low-bit-rate data source. Each frame is transmitted as a group of signal points. At the receiver, in order to demultiplex each such multiplexing frame for delivery to several corresponding ports serving relatively low-bit-rate data sinks, the receiver must be able to locate the beginning of each group of signal points.

SUMMARY OF THE INVENTION

One general feature of the invention is a communication system in which frame synchronization is maintained at the receiver by causing the sequence of signal points that results when the receiver incorrectly determines the start of each frame to be an impermissible sequence of the trellis code, and detecting the existence of the impermissible sequence by monitoring the rate of occurrence of non-zero difference between the minimum path metric and the minimum branch metric associated with a maximum likelihood decoding algorithm (for example the Viterbi algorithm) in the receiver.

Another general feature of the invention is an interleaver that changes the original sequence of signal points to a revised sequence for transmission and a deinterleaver that changes the received sequence of signal points in a manner that will restore the original sequence when the receiver is in frame synchronization, and will otherwise restore an impermissible sequence.

Preferred embodiments include the following features. The communication system is a trellis-coded modulation system. Each signal point is two-dimensional. The two-dimensional points are grouped into multi-dimensional points. Each frame has at least one multi-dimensional point. Each multi-dimensional point is 8 dimensional. The transmitter includes a multiplexer to receive information bits from more than one port and multiplex them such that the information bits are organized into groups corresponding to the frames of signal points, the bits from each port always appearing in the

same particular positions in each group. The information bits are transmitted at a rate of Q bits per signaling interval. The bits from a given port do not always occupy the same particular positions in each group of bits transmitted in a signal interval. When the rate of occurrence of non-zero difference between the minimum path metric and the minimum branch metric is greater than a predetermined threshold (e.g., 0.4), a synchronization loss signal is delivered.

The invention permits frame synchronization to be maintained without requiring any additional information to be transmitted. Since both the minimum path metric and the minimum branch metric are easily available in the receiver, frame synchronization can be maintained at almost no cost in system complexity. Frame synchronization information is available immediately at the receiver, and is accurate even under very noisy conditions. In embodiments that use interleaving, the performance of the decoder against correlated noise can also be improved by the interleaving.

Other advantages and features will become apparent from the following description of the preferred embodiment, and from the claims.

DESCRIPTION OF THE PREFERRED EMBODIMENT

We first briefly describe the drawings.

Drawings

FIG. **1** is a block diagram of a transmitter.

FIG. **2** is a block diagram of the encoders and grouping device of FIG. **1**.

FIG. **3** is a block diagram of a receiver for use with FIG. **1**.

FIG. **4** is a block diagram of the decoder of FIG. **3**.

FIG. **5** is a block diagram of the interleaver of FIG. **1**.

FIG. **6** is a block diagram of the deinterleaver of FIG. **4**.

FIG. **7** is a block diagram of the Viterbi algorithm device of FIG. **4**.

STRUCTURE AND OPERATION

Referring to FIG. **1**, in transmitter **10** the bits delivered from each of P different sending ports **12** (for example, P=8) at a rate of Q/P bits per signaling interval (where, for example, Q=7 and each signaling interval is 1/2743 seconds long) are combined in a multiplexer **16** to form a framed multiplexed serial bit stream to be sent over a channel **14**. The multiplexed bit stream is scrambled in a scrambler **17** and then delivered to encoders and grouping device **18** at a rate of Q bits per signaling interval (i.e., 7 bits per signaling interval in the present example). Multiplexer **16** also provides side framing information (indicated by dashed lines) to encoders and grouping device **18** and to an interleaver **19**. The bits appearing at the input of encoders and grouping device **18** with respect to a given signaling interval, for example, the nth signaling interval, are denoted $I1_n$ through IQ_n. The side framing information indicates which bits in the multiplexed serial bit stream are the initial bits in the frames of the multiplexed bit stream.

Based on the side framing information and on the information bits appearing with respect to a number N (for example, N=4) of successive signaling intervals (for example the 28 information bits $I1_m$ through IQ_m, for m=n, n+1, . . . , n+3), the encoders and grouping

device 18 deliver to interleaver 19, N pairs of in-phase and quadrature coordinates in series, one pair in each signaling interval, each pair corresponding to a point in a two-dimensional (2D) signal constellation. Interleaver 19 reorders the coordinate pairs based on the side framing information (in a manner to be described below), and delivers them to a modulator 20 to modulate a carrier. The modulated carrier is then pulse-shape filtered, and then D-to-A converted to an analog signal for transmission over channel 14 (as in a conventional Quadrature-Amplitude-Modulated (QAM) carrier system).

Referring to FIG. 2, encoders and grouping device 18 include a serial-to-parallel bit converter 29 which groups the incoming scrambled serial bitstream into blocks of NQ information bits based on the side framing information and sends them in parallel to differential encoder 30. The differentially encoded information bits are then passed through a convolutional encoder 32 which adds one redundant bit indicative of the current state of a finite state device represented by the convolutional encoder. The convolutionally encoded bits are then passed through a bit converter and block encoder 34. The block encoder encodes some of the input bits and adds $N-1$ additional bits; and the bit converter converts a set of bits into an equal number of bits.

The output bits of the bit converter and block encoder 34 are a set of NR point selection bits, where R is an integer equal to $Q+1$ (because bits have been added by the convolutional encoder and the block encoder). A bit grouping device and parallel-to-serial bit group converter 36 then organizes the NR coded bits into N groups denoted as $Z0_m$ through ZQ_m, $m=n,n+1,\ldots,n+N-1$, and delivers one group in each signaling interval to a 2D mapping table 38. For each combination of bits in a group, table 38 contains the corresponding pair of modulation coordinates which are then delivered to interleaver 19 (FIG. 1).

Because the next state of the finite state device represented by the convolutional encoder depends both on its current state and on the current information bits, the output bits of the convolutional encoder (and hence the transmitted signals) carry historical information about the sequence of information which is exploited at the receiver end of channel 14.

Referring to FIG. 3, in receiver 40, the received channel signal is passed through an A-to-D converter 42, an adaptive equalizer 44, and an adaptive demodulator 46. Equalized and demodulated coordinate pairs are delivered serially from demodulator 46 to a decoder 48. Decoder 48 feeds back preliminary decisions on the received coordinate pairs to equalizer/demodulator updating signal calculator 45. These preliminary decisions are processed in calculator 45 in a conventional manner to generate updating signals for the equalizer and demodulator, as disclosed in Falconer, "Jointly Adaptive Equalization and Carrier Recovery in Two-Dimensional Digital Communication Systems", Bell System Technical Journal, pp. 317-334, March, 1976, incorporated herein by reference. The preliminary decisions may be delayed. In that case the demodulator output will be delayed accordingly by delay element 47 before it is sent to calculator 45. Decoder 48 also deinterleaves the coordinate pairs and, after a delay of a number of signaling intervals, delivers to descrambler 51 final decisions of scrambled information bits which were sent. The descrambled bit stream is demultiplexed in demultiplexer 52 (based on side framing information delivered from decoder 48) into P bit streams, one delivered to each output port 54.

Referring to FIG. 4, in decoder 48 the interleaved serial coordinate pairs are delivered to a deinterleaver 55 which, as long as frame synchronization has not been lost, restores them to their original non-interleaved order, based on side framing information from a Viterbi algorithm device 60. The interleaved serial coordinate pairs are also delivered to a slicer 56 which feeds back the preliminary decisions to equalizer and demodulator 45. The deinterleaved pairs are delivered to Viterbi algorithm device 60 which, after some delay, delivers N final coordinate pair decisions in parallel for every block of N signaling intervals. The Viterbi algorithm device 60 also derives the side framing information in a manner described below and delivers it to deinterleaver 55 and demultiplexer 52. Converter 62 applies one coordinate pair in each signaling interval to a bit mapping table 64. For each block of N coordinate pairs applied to table 64, the corresponding N groups of R decision bits are grouped together in serial-to-parallel bit group converter 65 and delivered to a bit deconverter and block decoder 66 and then to a differential decoder 68. The deconverter and decoder perform reverse conversion and decoding from those performed at the transmitter. A parallel-to-serial bit converter 69 then provides the original scrambled information bitstream to the descrambler 51.

The transmitter and receiver are implemented by programming a microprocessor and signal processors interconnected in the way disclosed in U.S. patent application Ser. No. 586,681, filed Mar. 6, 1984, incorporated herein by reference.

In a preferred embodiment, to send 7 bits per signaling interval using a 64-state, 8D code, as set forth in the Wei patent application, incorporated by reference above, the transmitter takes the 28 information bits which appear at the output of scrambler 17 in each block of four signaling intervals and encodes them into four 2D points (which together define an 8D point) drawn from a 2D constellation having 160 points.

Because there are 8 ports and because 28 is not an integral multiple of 8, it is impossible to arrange for the bits drawn from a given sending port 12 to always appear in the same particular positions in each 28-bit block corresponding to an 8D point. However, by defining a multiplexing frame of 56 bits corresponding to two 28-bit blocks, and by drawing seven bits in turn from each sending port to make up the 56-bit frame, then the bits drawn from a given sending port can always occupy the same particular positions in each frame. By synchronizing receiver 40 to identify the beginning of each multiplexing frame, the demultiplexer can deliver to the corresponding receiving port 54 the bits which appear in those particular positions in each frame.

Referring to FIG. 5, the 2D points delivered by the encoders and grouping device 18 are denoted S_n, where $n=1, 2, \ldots$ is the order of the signaling intervals. Each multiplexing frame comprises eight 2D points (i.e., two 8D points). For example, the first multiplexing frame is made up of $S_1 \ldots S_8$, the second begins with S_9, and so on.

In order for the receiver 40 to identify the beginning of each multiplexing frame, interleaver 19 reorders the eight coordinate pairs in each frame as follows. Interleaver 19 has a random access memory (RAM) 70 that comprises eight storage elements 72. Each element can hold one coordinate pair. Each of these eight elements

has an address (indicated by reference numeral **71**) from #**1** through #**8**. And they can be accessed in a random order. The element being currently written into is determined by the address contained in an input address register **73**. And the element being currently read out is determined by the address contained in an output address register **75**. The coordinate pairs at the output of the encoders and grouping device **18** are written into the RAM **70** based on a cyclic input address sequence, #**1**, #**2**, #**3**, #**4**, #**5**, #**6**, #**7**, #**8**, starting with #**1**. The coordinate pair S_1 is thus written into the storage element #**1** in the signaling interval **1**. S_2 is written into the storage element #**2** in the signaling interval **2**. S_9 is written into the storage element #**1** in the signaling interval **9**, and so on.

Starting from signaling interval **5**, the coordinate pairs are read out of the RAM **70** based on a cyclic output address sequence, #**1**, #**5**, #**2**, #**6**, #**3**, #**7**, #**4**, #**8**, starting with #**1**. The coordinate pair S_1 is thus read out of the element #**1** in the signaling interval **5**. The coordinate pair S_5 is read out of the element #**5** in the signaling interval **6**. The coordinate pair S_9 is read out of the element #**1** again in the signaling interval **13**, and so on. FIG. **5** illustrates the situation at the beginning of signaling interval **17**. At that moment, RAM **70** contains the coordinate pairs S_9, S_{10}, S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, and S_{16} stored in the elements #**1**, #**2**, #**3**, #**4**, #**5**, #**6**, #**7**, and #**8**, respectively. The input address register contains the address #**1**. The current input coordinate pair S_{17} will be written into the element #**1**. The coordinate pair S_9 currently stored in that element will be erased. The output address register contains the address #**3**. The coordinate pair S_{11} currently stored in the element #**3** will be read out. Also shown in FIG. **5** are the sequence of coordinate pairs that have already been read out of the RAM **70** and the next eight coordinate pairs that are going to be written into the RAM **70** in the next eight signaling intervals. At the end of the signaling interval **17**, the RAM **70** contains the coordinate pairs S_{17}, S_{10}, S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, and S_{16}, stored in the elements #**1**, #**2**, #**3**, #**4**, #**5**, #**6**, #**7**, and #**8**, respectively. And the addresses contained in the input and output address registers are respectively updated to #**2** and #**7** based on the cyclic input and output address sequences mentioned above.

Referring to FIG. **6**, at the receiver, deinterleaver **55** reverses the interleaving process to restore the received coordinate pairs into their original order S_1, S_2, S_3, . . . , assuming that the receiver knows where the beginning of each multiplexing frame is.

The deinterleaver **55** has a configuration identical to that of the interleaver **19**. It has a RAM **80** that comprises eight storage elements **82**, an input address register **83**, and an output address register **85**. The eight elements of the RAM **80** have addresses from #**1** though #**8** (as indicated by reference numeral **81**).

The coordinate pairs at the output of the demodulator **46** are written into the RAM **80** based on a cyclic input address sequence, #**1**, #**5**, #**2**, #**6**, #**3**, #**7**, #**4**, #**8**, starting with #**1**. The first coordinate pair in each received frame of eight coordinate pairs at the output of the demodulator **46** is thus always written into the element #**1** when the receiver knows where the beginning of each frame is. For notational convenience, assume that the first received coordinate pair S_1 is written into the element #**1** in the signaling interval **1** of the receiver. Note that there may be a delay in the signaling interval **1** of the receiver as compared to that of the transmitter because of the propagation time and the processing time that elapses ahead of decoder **48**. Starting from the signaling interval **5** of the receiver, the coordinate pairs are read out of the RAM **80** based on a cyclic output address sequence #**1**, #**2**, #**3**, #**4**, #**5**, #**6**, #**7**, #**8**, starting with #**1**. The coordinate pair S_1 is thus read out of the element #**1** in the signaling interval **5** of the receiver. The coordinate pair S_2 is read out of the element #**2** in the signaling interval **6**. The coordinate pair S_9 is read out of the element #**1** again in the signaling interval **13**, and so on. FIG. **6** illustrates the situation at the beginning of the signaling interval **17** of the receiver. At that moment, the RAM **80** contains the coordinate pairs S_9, S_{10}, S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, and S_{16} stored in the elements #**1**, #**2**, #**3**, #**4**, #**5**, #**6**, #**7**, and #**8**, respectively. The input address register contains the address #**1**. The current input coordinate pair S_{17} will be written into the element #**1**. The coordinate pair S_9 currently stored in the element #**1** will be erased. The output address register contains the address #**5**. The coordinate pair S_{13} currently stored in the element #**5** is going to be read out. Also shown in FIG. **6** are the sequence of coordinate pairs that have already been read out of the RAM **80**, and the next eight coordinate pairs that are going to be written into RAM **80** in the next eight signaling intervals.

At the end of signaling interval **17**, RAM **80** contains the coordinate pairs S_{17}, S_{10}, S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, and S_{16}, stored in the elements #**1**, #**2**, #**3**, #**4**, #**5**, #**6**, #**7**, and #**8**, respectively. The addresses contained in the input and output address registers are respectively updated to #**5** and #**6** based on the last mentioned cyclic input and output address sequences.

Referring to FIG. **7**, Viterbi algorithm device **60** includes a decision device **90** that uses the Viterbi algorithm and the incoming stream of deinterleaved serial coordinate pairs to decide which coordinate pairs were sent. The coordinate pair decisions are delivered (after some delay) to converter **62** (FIG. **4**). Decision device **90** operates in a manner disclosed in the Wei application (incorporated by reference above). In order to identify the beginning of each multiplexing frame, device **90**, in the course of its operation with respect to each received 8D point, also generates the minimum current 8D branch metric that represents the squared Euclidean distance between the received 8D point and the nearest 8D point in the 8D constellation.

In extending the trellis paths in the decision device **90**, each of the 64 current states of the trellis code is associated with a current path metric. These current path metrics are normalized. That is, the minimum of these current path metrics is zero. For each received 8D point, these current path metrics are updated as follows. For each of the 64 next states, a sum is formed for each transition from a current state leading to that next state by adding the associated current path metric and the associated 8D branch metric. These sums are compared and the smallest sum becomes the unnormalized next path metric associated with that next state. The minimum of the 64 unnormalized next path metrics is then determined and delivered to loss of frame synchronization monitor **101**. This minimum unnormalized next path metric is also used in the decision device **90** to normalize the next path metric associated with each next state. These normalized next path metrics will then be referred to as the current path metrics for the next received 8D point. The minimum unnormalized next path metric represents the squared Euclidean distance

between the received sequence of coordinate pairs and the nearest permissible sequence of 8D points through the trellis.

The loss of frame synchronization monitor **101** receives the current minimum 8D branch metric and the minimum unnormalized next path metric, and, based on them, detects if frame synchronization has been lost. If loss is detected, a loss signal is sent to a resynchronization circuit **96**. When the circuit **96** receives the loss signal, it tells the deinterleaver **55** and the demultiplexer **52** to shift backward (or forward) one 2D point in the positions that are treated as the beginnings of the frames. This shifting process is repeated until no loss signal is received. Since there are eight 2D points in each frame, the process will be repeated at most seven times. Alternatively if a reverse channel from the receiver to the transmitter is available, the circuit **96** can instruct the transmitter to send a known sequence of signal points to reestablish the frame synchronization.

Monitor **101** includes a subtracter **100** that forms the difference between the current minimum 8D branch metric and the minimum unnormalized next path metric. This difference is sent to an RNZ counter **102**. Various ways can be used in the RNZ counter **102** to count the rate of occurrence of nonzero difference. One method is described below. RNZ counter **102** is reinitialized to zero at the beginning of each successive block of 100 8D points, and calculates the proportion of 8D points in each block for which a non-zero difference has occurred. It does this by counting the number of nonzero differences from subtracter **100** and dividing the count by 100. If this proportion, called RNZ, is greater than 0.4 for three successive blocks of 100 8D points, RNZ counter **102** issues the loss signal to circuit **96**.

That the frame synchronization can be maintained by monitoring the RNZ can be seen as follows. When the receiver loses frame synchronization, it slips backward (or forward) one or more 2D points in the position that it treats as the beginning of the frame. For example, if it slips backward by one 2D point, it would erroneously determine that the first and second frames at the input of the deinterleaver **55** as being made up of the following 2D points (assuming, for ease of discussion, that the received points are not noise altered):

First Frame

$S_5S_2S_6S_3 \quad S_7S_4S_8S_9$

Second Frame

$S_{13}S_{10}S_{14}S_{11} \quad S_{15}S_{12}S_{16}S_{17}$

(Successive signal points are shown from left to right.) The deinterleaver **55** would then deliver the following deinterleaved series of 2D points (or sequence of 8D points) to the Viterbi algorithm device **60**:

First Frame

$\underbrace{S_5S_6S_7S_8}_{\text{8D point \#1}} \quad \underbrace{S_2S_3S_4S_9}_{\text{8D point \#2}}$

Second Frame

-continued

$\underbrace{S_{13}S_{14}S_{15}S_{16}}_{\text{8D point \#3}} \quad \underbrace{S_{10}S_{11}S_{12}S_{17}}_{\text{8D point \#4}}$

(Successive signal points are shown from left to right.)

This sequence of 8D points is different from the original sequence at the transmitter, and from any shifted version of the original sequence. The sequence is also not a permissible sequence of the trellis code. This is also the case when the receiver slips backward by two, three, . . . , or seven 2D points, which, together with one 2D-point slip, cover all the possible slips.

In the case where the sequence of received 8D points input to the Viterbi algorithm device **60** (assuming the removal of the noise component from each received 8D point) is not a permissible sequence of the trellis code, the probability that the 8D point, closest to the current received noise-altered 8D point and corresponding to the minimum current 8D branch metric, is not associated with a transition from the current state with the minimum current path metric is exactly one-half, because each 8D point is associated with transitions from exactly half of the 64 states of the trellis code. This probability is the same as the rate RNZ at which nonzero difference occurs between the minimum current 8D branch metric and the minimum unnormalized next path metric.

By contrast, when frame synchronization has not been lost, the minimum 8D branch metric corresponds to the preliminary decision at the output of slicer **56**. If the output of subtracter **100** is not zero, it implies that either the current preliminary decision or at least one of the recent past preliminary decisions is wrong. Thus the value RNZ corresponds to the symbol error rate of preliminary decisions (SER). In fact the RNZ has been shown by simulation to be smaller than the SER, and SER is only 0.3 even when the corresponding block error rate of final decisions (each block comprises 36 8D-points) is approximately 0.2. Therefore, the values of RNZ when frame synchronization is and is not lost, respectively, are well separated on opposite sides of the 0.4 threshold used by counter **102**.

Without the interleaver **19** and deinterleaver **55**, the sequence of 8D points input to the Viterbi algorithm device **60** would be a shifted version of the transmitted sequence and thus would be a permissible sequence of the trellis code when the receiver slips four 2D points, a condition which could not be detected by monitoring the Viterbi algorithm device **60**. And the demultiplexer then could not function properly.

Among the advantages of the invention are the following. No additional bit is transmitted for frame synchronization. Since both the minimum 8D branch metric and the minimum unnormalized path metric are easily available in the receiver, it is simple to acquire the framing information. Both the minimum 8D branch metric and the minimum unnormalized path metric are available once the receiver starts. The framing information is thus immediately available. The invention works even when the transmission medium is very noisy. The interleaver can further enhance the performance of the trellis code when the noise components contained in the sequence of received signal points are correlated.

Other embodiments are within the following claims.

For example, any type of interleaver can be used to interleave the 2D points at the output of the encoders

and grouping device **18** as long as the following statement is valid. When the receiver fails to identify the beginning of each multiplexing frame, the sequence of 8D points obtained at the output of the corresponding deinterleaver is no longer a permissible sequence of the trellis code.

Interleaving is not required in systems where loss of frame synchronization causes resulting sequences of signal points to be invalid under the code.

The invention can be used with 2D trellis-coded systems that have a multiplexed framing structure, or with multi-dimensional trellis-coded systems that are other than the 64-state, 8D code, or with multi-dimensional systems in which the original bit stream is not multiplexed.

The ports served by the system can respectively operate at different bit rates.

I claim:

1. Apparatus for maintaining frame synchronization in a communication system comprising

a transmitter that sends a sequence of signal points in successive time intervals, said signal points being drawn from a constellation of available signal points such that said sequence is one of a set of permissible sequences that is smaller than the set of all possible sequences of said signal points, said sequence of signal points being organized as a series of frames, each frame beginning at a predetermined time, and

a receiver that determines said predetermined time when each said frame begins in order to maintain frame synchronization with said transmitter, said receiver comprising

a decision device for determining said sequence of signal points which were sent by determining the minimum next path metric based on current path metrics and current branch metrics, and

means for detecting and monitoring the rate of occurrence of non-zero difference between said minimum next path metric and the minimum of said current branch metrics as an indication of loss of frame synchronization.

2. The apparatus of claim **1** wherein said apparatus further comprises

an interleaver for changing the original said sequence of signal points to a revised sequence for transmission, and

a deinterleaver for changing the received sequence of signal points in a manner that will restore said original sequence when said receiver is in frame synchronization with said transmitter, and will restore a sequence not within said set of permissible sequences when frame synchronization has been lost.

3. Apparatus for maintaining frame synchronization in a communication system comprising

a transmitter that sends a sequence of signal points in successive time intervals, said signal points being drawn from a constellation of available signal points such that said sequence is one of a set of permissible sequences that is smaller than the set of all possible sequences of said signal points, said sequence of signal points being organized as a series of frames, each frame beginning at a predetermined time,

a receiver that determines said predetermined time when each said frame begins in order to maintain frame synchronization with said transmitter,

an interleaver for changing the original said sequence of signal points to a revised sequence for transmission,

a deinterleaver for changing the received sequence of signal points in a manner that will restore said original sequence when said receiver is in frame synchronization with said transmitter, and will restore a sequence not within said set of permissible sequences when frame synchronization has been lost, and

means for detecting that said sequence of signal points is not within said set of permissible sequences as an indication that synchronization has been lost.

4. The apparatus of claim **3** wherein said means for detecting comprises

a decision device for determining said sequence of signal points which were sent, by determining the minimum next path metric based on current path metrics and current branch metrics, and

means for detecting and monitoring the rate of occurrence of non-zero difference between said minimum next path metric and the minimum of said current branch metrics as an indication of loss of frame synchronization.

5. The apparatus of claim **1** or **3** wherein said communication system comprises a trellis-coded modulation system.

6. The apparatus of claim **1** or **3** wherein said communication system is a multi-dimensional, trellis-coded modulation system, each said signal point is a two-dimensional signal point, said two-dimensional signal points are grouped into multi-dimensional signal points, and each said frame comprises at least one said multi-dimensional signal point.

7. The apparatus of claim **6** wherein each said multi-dimensional signal point is 8 dimensional.

8. The apparatus of claim **7** wherein each said frame comprises two 8-dimensional points.

9. The apparatus of claim **1** or **3** wherein

said sequence of signal points corresponds to a stream of information bits to be transmitted, and

said transmitter includes multiplexer means to receive said information bits from a plurality of ports,

said information bits are organized into groups corresponding to said frames of signal points, the bits from each given said port always appearing in the same particular positions in each said group.

10. The apparatus of claim **9** wherein

said information bits are transmitted at a rate of Q bits per signaling interval,

and wherein the bits from a given said port do not occupy the same particular positions in groups of Q bits transmitted in said signaling intervals.

11. The apparatus of claim **10** wherein

there are eight said ports,

Q is 7, and

each said frame comprises 56 said bits.

12. The apparatus of claim **1** or **4** wherein said detecting and monitoring means deliver a synchronization loss signal when said rate of occurrence of non-zero difference with respect to a plurality of said time intervals is greater than a predetermined threshold.

13. The apparatus of claim **12** wherein said predetermined threshold is 0.4.

* * * * *

EXHIBIT E

United States Patent [19]

Gallager

[11] **Patent Number:** **4,755,998**

[45] **Date of Patent:** **Jul. 5, 1988**

[54] **CODED MODULATION SYSTEM**

[75] Inventor: **Robert G. Gallager,** Lexington, Mass.

[73] Assignee: **Codex Corporation,** Mansfield, Mass.

[21] Appl. No.: **911,664**

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Related U.S. Application Data

[63] Continuation of Ser. No. 577,044, Feb. 6, 1984, abandoned.

[51] **Int. Cl.**⁴ **H04L 5/12;** G06F 11/10

[52] **U.S. Cl.** **371/30;** 371/43; 375/27; 375/39

[58] **Field of Search** 371/30, 43, 44, 45; 375/25, 27, 34, 39

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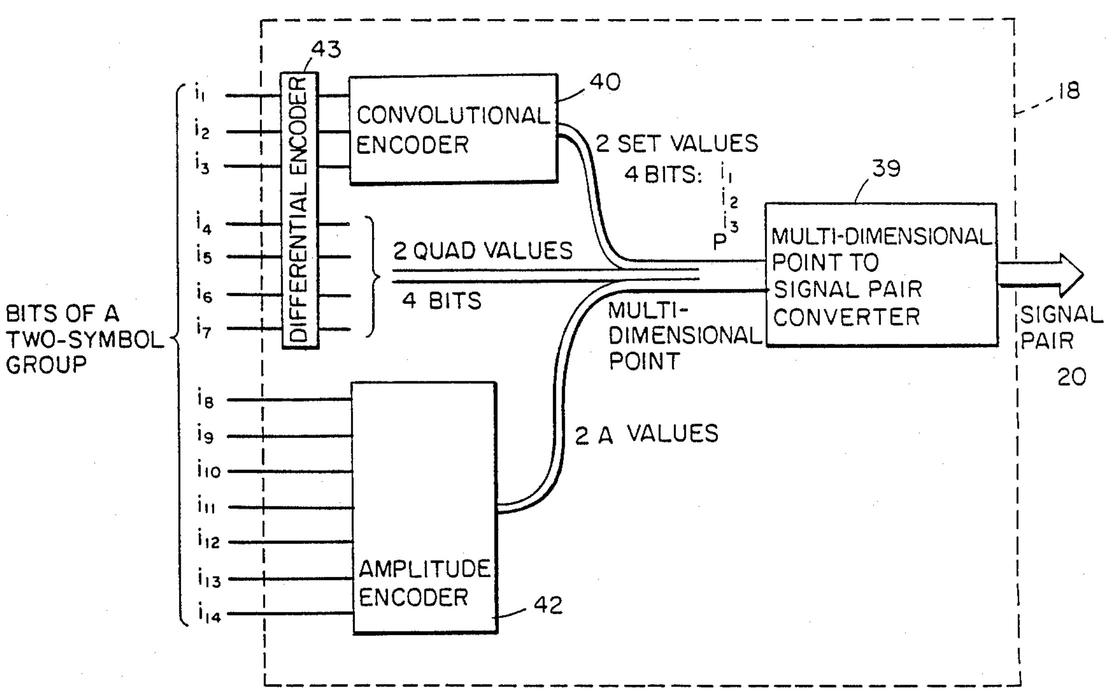
Primary Examiner—Charles E. Atkinson

[57] **ABSTRACT**

In a modulation system for sending digital symbols over a band-limited channel in accordance with a sequence of multi-dimensional points each composed of a plurality of two-dimensional modulation signal points, and each selected from an available alphabet of the multi-dimensional points by an encoder on the basis of a group of the digital symbols, the improvement which includes circuitry for accumulating the symbols of each group, and circuitry for thereafter selecting the multi-dimensional point for the group, and in which the available alphabet includes a plurality of subsets of the multi-dimensional points, and the subset from which the multi-dimensional point is selected for each group depends on the subset from which the multi-dimensional point is selected for another one of the groups.

14 Claims, 6 Drawing Sheets



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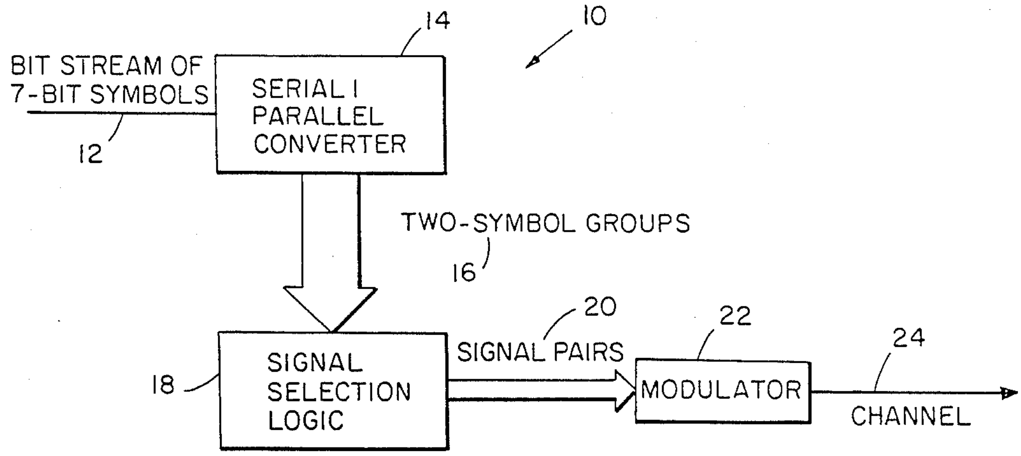
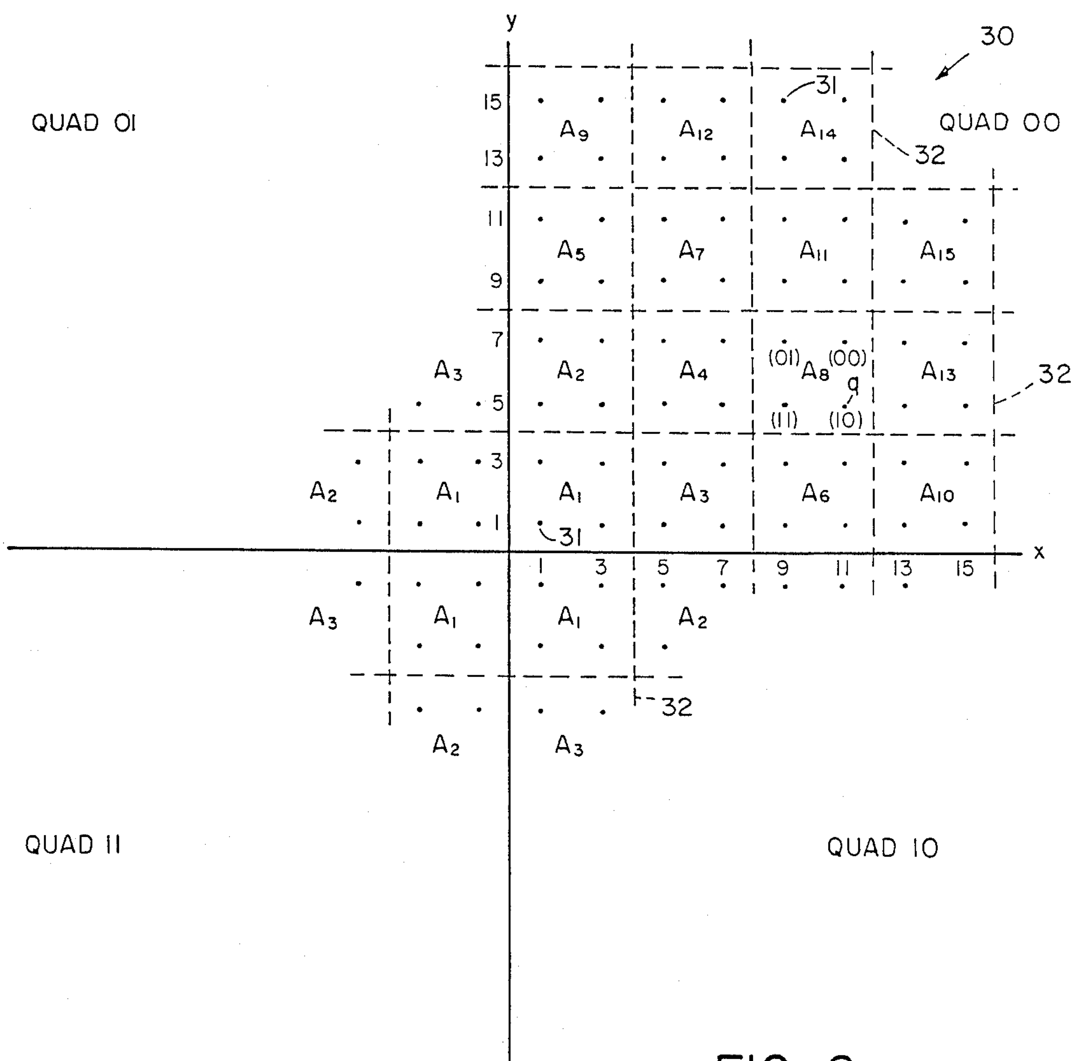


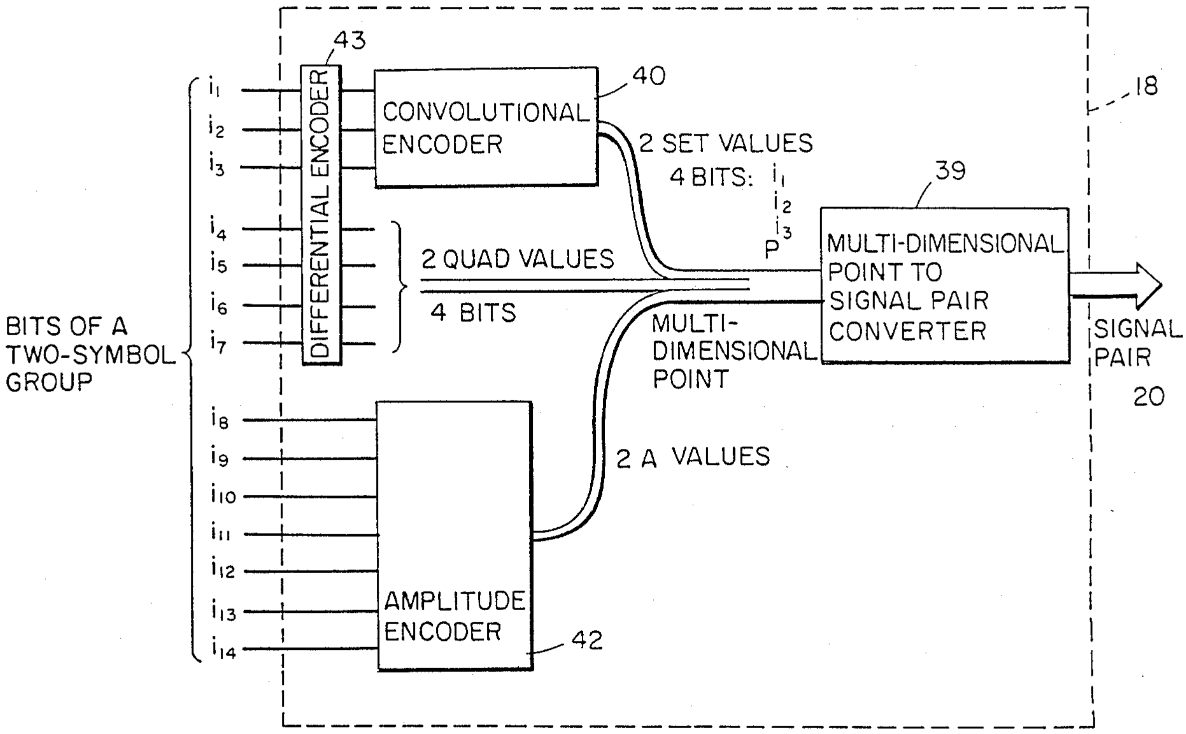
10
14
BIT STREAM OF 7-BIT SYMBOLS
12
SERIAL I PARALLEL CONVERTER
TWO-SYMBOL GROUPS
16
18
SIGNAL SELECTION LOGIC
20
SIGNAL PAIRS
22
MODULATOR
24
CHANNEL

FIG. 1



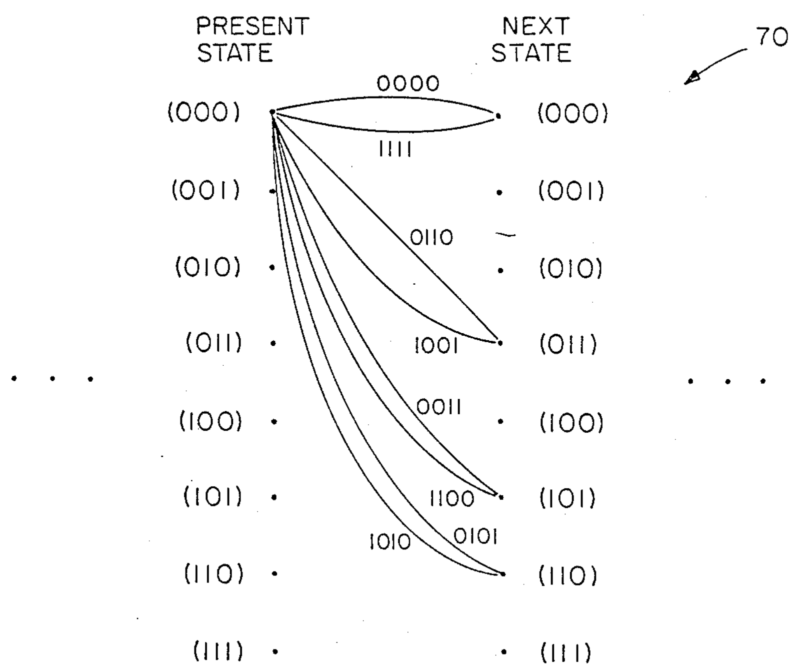
30
QUAD 01
QUAD 00
QUAD 11
QUAD 10
y
x
31
32
(01)
(00)
(11)
(10)
q

FIG. 2



43
DIFFERENTIAL ENCODER
CONVOLUTIONAL ENCODER
40
18
2 SET VALUES
4 BITS: i1 i2 i3 P
39
MULTI-DIMENSIONAL POINT TO SIGNAL PAIR CONVERTER
2 QUAD VALUES
4 BITS
MULTI-DIMENSIONAL POINT
SIGNAL PAIR
20
BITS OF A TWO-SYMBOL GROUP
i1
i2
i3
i4
i5
i6
i7
i8
i9
i10
i11
i12
i13
i14
2 A VALUES
AMPLITUDE ENCODER
42

FIG. 3



PRESENT STATE
NEXT STATE
70
0000
1111
0110
1001
0011
1100
1010
0101
(000)
(001)
(010)
(011)
(100)
(101)
(110)
(111)

FIG. 5

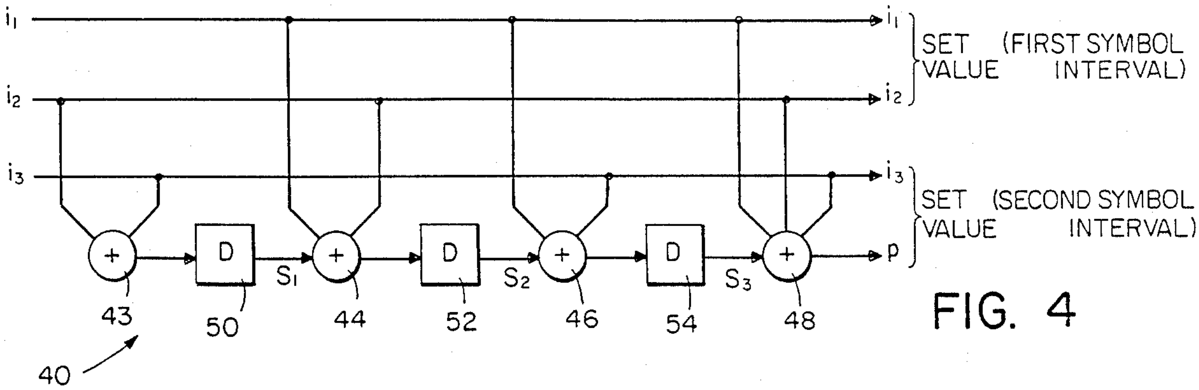


FIG. 4

PRESENT STATE $S_1S_2S_3$	$i_1 i_2 i_3$	NEXT STATE $S_1S_2S_3$	$i_1 i_2 i_3 p$	PRESENT STATE $S_1S_2S_3$	$i_1 i_2 i_3$	NEXT STATE $S_1S_2S_3$	$i_1 i_2 i_3 p$
000	000	000	0000	100	000	010	0000
000	111	000	1111	100	111	010	1111
000	001	101	0011	100	001	111	0011
000	110	101	1100	100	110	111	1100
000	010	110	0101	100	010	100	0101
000	101	110	1010	100	101	100	1010
000	011	011	0110	100	011	001	0110
000	100	011	1001	100	100	001	1001
001	000	000	0001	101	000	010	0001
001	111	000	1110	101	111	010	1110
001	001	101	0010	101	001	111	0010
001	110	101	1101	101	110	111	1101
001	010	110	0100	101	010	100	0100
001	101	110	1011	101	101	100	1011
001	011	011	0111	101	011	001	0111
001	100	011	1000	101	100	001	1000
010	000	001	0000	110	000	011	0000
010	111	001	1111	110	111	011	1111
010	001	100	0011	110	001	110	0011
010	110	100	1100	110	110	110	1100
010	010	111	0101	110	010	101	0101
010	101	111	1010	110	101	101	1010
010	011	010	0110	110	011	000	0110
010	100	010	1001	110	100	000	1001
011	000	001	0001	111	000	011	0001
011	111	001	1110	111	111	011	1111
011	001	100	0010	111	001	110	0010
011	110	100	1101	111	110	110	1101
011	010	111	0100	111	010	101	0100
011	101	111	1011	111	101	101	1011
011	011	010	0111	111	011	000	0111
011	100	010	1000	111	100	000	1000

FIG. 6

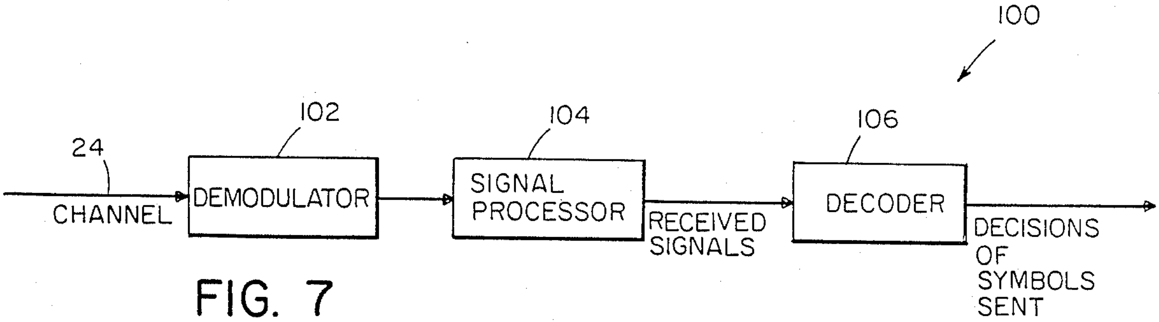


FIG. 7

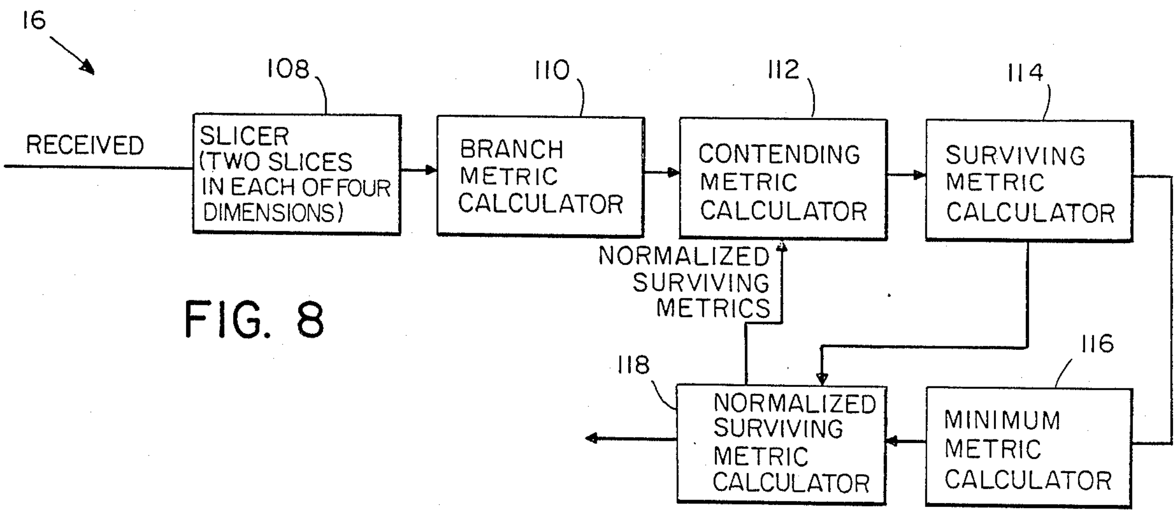


FIG. 8

$$\hat{m}(000,000)=m(000)+b(000),$$
$$\hat{m}(000,001)=m(000)+b(011),$$
$$\hat{m}(000,110)=m(000)+b(101),$$
$$\hat{m}(000,011)=m(000)+b(110);$$

$$\hat{m}(001,000)=m(001)+b(001),$$
$$\hat{m}(001,101)=m(001)+b(010),$$
$$\hat{m}(001,110)=m(001)+b(100),$$
$$\hat{m}(001,011)=m(001)+b(111);$$

$$\hat{m}(010,001)=m(010)+b(000),$$
$$\hat{m}(010,100)=m(010)+b(011),$$
$$\hat{m}(010,111)=m(010)+b(101),$$
$$\hat{m}(010,010)=m(010)+b(110);$$

$$\hat{m}(011,001)=m(011)+b(001),$$
$$\hat{m}(011,100)=m(011)+b(010),$$
$$\hat{m}(011,111)=m(011)+b(100),$$
$$\hat{m}(011,010)=m(011)+b(111);$$

$$\hat{m}(000,010)=m(100)+b(000),$$
$$\hat{m}(000,111)=m(100)+b(011),$$
$$\hat{m}(100,100)=m(100)+b(101),$$
$$\hat{m}(100,001)=m(100)+b(110);$$

$$\hat{m}(101,010)=m(101)+b(001),$$
$$\hat{m}(101,111)=m(101)+b(010),$$
$$\hat{m}(101,100)=m(101)+b(100),$$
$$\hat{m}(101,001)=m(101)+b(111);$$

$$\hat{m}(110,011)=m(110)+b(000),$$
$$\hat{m}(110,110)=m(110)+b(011),$$
$$\hat{m}(110,101)=m(110)+b(101),$$
$$\hat{m}(110,000)=m(110)+b(110);$$

$$\hat{m}(111,011)=m(111)+b(001),$$
$$\hat{m}(111,110)=m(111)+b(010),$$
$$\hat{m}(111,101)=m(111)+b(100),$$
$$\hat{m}(111,000)=m(111)+b(111);$$

FIG. 9

$$\hat{m}(000) = \min[\hat{m}(000,000), \hat{m}(001,000), \hat{m}(110,000), \hat{m}(111,000)],$$

$$\hat{m}(001) = \min[\hat{m}(010,001), \hat{m}(011,001), \hat{m}(100,001), \hat{m}(101,001)],$$

$$\hat{m}(010) = \min[\hat{m}(010,010), \hat{m}(011,010), \hat{m}(100,010), \hat{m}(101,010)],$$

$$\hat{m}(011) = \min[\hat{m}(000,011), \hat{m}(001,011), \hat{m}(110,011), \hat{m}(111,011)],$$

$$\hat{m}(100) = \min[\hat{m}(010,100), \hat{m}(011,100), \hat{m}(100,100), \hat{m}(101,100)],$$

$$\hat{m}(101) = \min[\hat{m}(000,101), \hat{m}(001,101), \hat{m}(110,101), \hat{m}(111,101)],$$

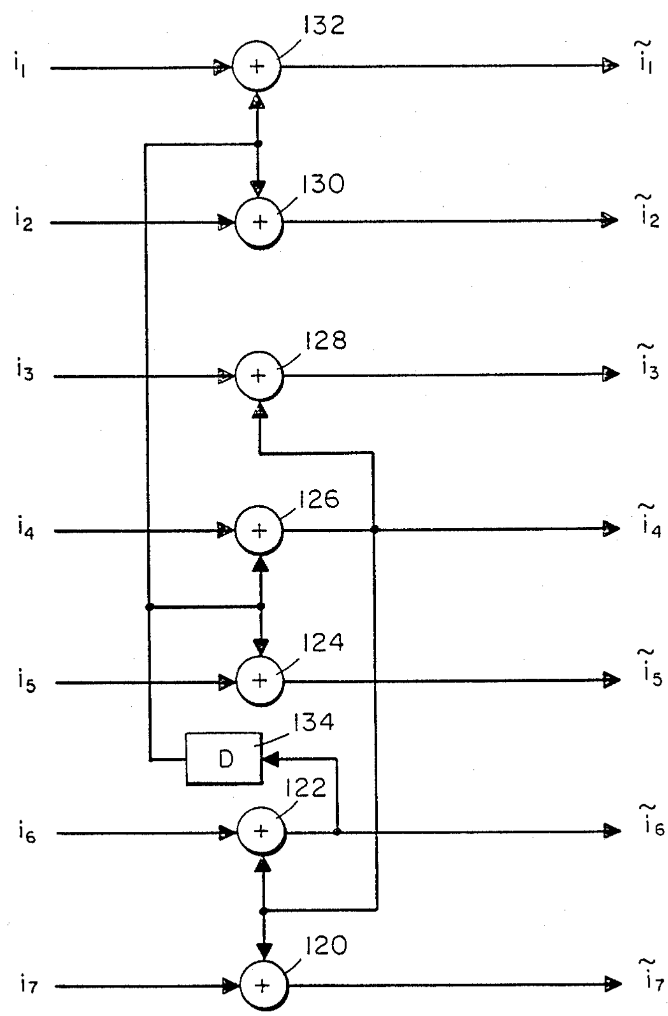
$$\hat{m}(110) = \min[\hat{m}(000,110), \hat{m}(001,110), \hat{m}(110,110), \hat{m}(111,110)],$$

$$\hat{m}(111) = \min[\hat{m}(010,111), \hat{m}(011,111), \hat{m}(100,111), \hat{m}(101,111)].$$

FIG. 10

$i_1^{(1)}$	$p^{(1)}$	$p^{(2)}$	$p^{(3)}$	$i_1^{(1)}$	$p^{(1)}$	$i_1^{(2)}$	$p^{(4)}$
$i_2^{(1)}$	$p^{(1)}$	$p^{(3)}$	$p^{(4)}$	$i_2^{(1)}$	$p^{(1)}$	$i_3^{(2)}$	$p^{(5)}$
$i_3^{(1)}$	$p^{(1)}$	$p^{(2)}$	$p^{(4)}$	$i_2^{(1)}$	$p^{(1)}$	$i_1^{(2)}$	$p^{(2)}$
$i_1^{(1)}$	$i_2^{(1)}$	$p^{(2)}$	$p^{(4)}$	$i_3^{(1)}$	$p^{(1)}$	$i_1^{(2)}$	$p^{(3)}$
$i_1^{(1)}$	$i_3^{(1)}$	$p^{(3)}$	$p^{(4)}$	$i_3^{(1)}$	$p^{(1)}$	$i_2^{(2)}$	$p^{(5)}$
$i_2^{(1)}$	$i_3^{(1)}$	$p^{(2)}$	$p^{(3)}$	$i_2^{(1)}$	$p^{(1)}$	$i_1^{(3)}$	$p^{(5)}$
$i_1^{(1)}$	$i_2^{(1)}$	$i_3^{(1)}$	$p^{(1)}$	$i_2^{(1)}$	$i_3^{(1)}$	$i_1^{(2)}$	$p^{(4)}$
$i_1^{(1)}$	$i_3^{(1)}$	$i_1^{(2)}$	$p^{(2)}$	$i_2^{(1)}$	$i_3^{(1)}$	$i_2^{(2)}$	$i_1^{(3)}$
$i_1^{(1)}$	$i_3^{(1)}$	$i_2^{(2)}$	$i_3^{(2)}$	$i_2^{(1)}$	$i_3^{(1)}$	$i_3^{(2)}$	$p^{(5)}$
$i_1^{(1)}$	$i_2^{(1)}$	$i_1^{(2)}$	$p^{(3)}$	$i_2^{(1)}$	$p^{(1)}$	$i_2^{(2)}$	$i_3^{(2)}$
$i_1^{(1)}$	$p^{(1)}$	$i_2^{(2)}$	$i_1^{(3)}$	$i_3^{(1)}$	$p^{(1)}$	$i_3^{(2)}$	$i_1^{(3)}$

FIG. 11



i_1
i_2
i_3
i_4
i_5
i_6
i_7
132
130
128
126
124
134
D
122
120
$\tilde{i}_1$
$\tilde{i}_2$
$\tilde{i}_3$
$\tilde{i}_4$
$\tilde{i}_5$
$\tilde{i}_6$
$\tilde{i}_7$

FIG. 12

CODED MODULATION SYSTEM

This is a continuation of co-pending application Ser. No. 577,044 filed on Feb. 6, 1984, now abandoned.

BACKGROUND OF THE INVENTION

This invention relates to transmitting digital symbols over a band-limited channel by modulating a carrier in accordance with a sequence of signals selected from an available signal constellation by a coding technique which introduces dependencies between signals in the sequence to increase immunity to noise (i.e., to achieve a so-called "coding gain" compared with an uncoded system).

Csajka et al., U.S. Pat. No. 4,077,021, and Ungerboeck, "Channel Coding with Multilevel/Phase Signals," IEEE Transactions on Information Theory, Vol. IT-28, No 1, January, 1982, incorporated herein by reference, disclose a coding system in which a conventional two-dimensional signal constellation having 2^N signal points (the number needed for simple mapping of symbols having N bits in an uncoded system in which no dependencies are introduced between signal points) is doubled in size to 2^{N+1} signal points. An encoder introduces a degree of redundancy by adding one bit of information to each N-bit symbol, based on the state of a finite-state memory in the encoder, and the resulting N+1 bits for each symbol are mapped into one of the 2^{N+1} possible signal points in the constellation. The signal points are organized into subsets which are disjointed (i e., have no signal points in common) and arranged so that the minimum distance between two signal points belonging to one subset is greater than the minimum distance between any two signal points in the constellation. The state of the finite state memory is arranged to depend on the subsets from which past signals were drawn. The encoder performs a coding function by using the state of the finite state memory as the basis for determining the subset from which each signal is to be drawn. Because this coding effectively permits only certain sequences of signals to be transmitted, each signal carries (in the form of the identity of the subset from which it is drawn) historical information which is exploited at the receiver to decode the sequence of received signals using a maximum likelihood sequence estimation technique (e.g., one based on the Viterbi Algorithm, as described in Forney, "The Viterbi Algorithm," Proceedings of the IEEE, Vol. 61, No. 3, March, 1973, incorporated herein by reference).

Another coding system, disclosed in copending patent application. U.S. Ser, No. 439,740, Forney, uses a signal constellation having more than 2^N but fewer than 2^{N+1} signal points organized into two subsets which are partially overlapping and partially disjointed. A two-state encoder is arranged in such a way that on average only a portion of the sent signals carry historical information (i.e., include redundancy).

Another copending patent application, U.S. Ser. No. 485,069, U.S. Pat. No. 4,597,090 issued 6/24/86, Forney, shows systems in which the symbols to be sent are taken in groups, each having at least two symbols. Each group is encoded independently into a multi-dimensional point corresponding in turn to two or more two-dimensional signal points. The set of multi-dimensional points from which each multi-dimensional point may be drawn is independent of the two-dimensional signal points sent for any other group of symbols, but there is an interdependence among the signal points drawn for a given group.

SUMMARY OF THE INVENTION

In general the invention features, in one aspect, an improvement in a modulation system for sending digital symbols over a band-limited channel in accordance with a sequence of multi-dimensional points each composed of a plurality of two-dimensional modulation signal points, and each selected from an available alphabet of the multi-dimensional points by an encoder on the basis of a group of the digital symbols, the improvement including circuitry for accumulating the symbols of each group, and circuitry for thereafter selecting the multi-dimensional point for the group, and wherein the available alphabet includes a plurality of subsets of the multi-dimensional points and the subset from which the multi-dimensional point is selected for each group depends on the subset from which the multi-dimensional point is selected for another group.

In preferred embodiments the accumulating circuitry is arranged to add less than one bit per symbol interval of information about the dependencies among the selected multi-dimensional points (preferably no more than one-half bit per symbol interval); there is a decoder for deciding which multi-dimensional points were sent by applying a maximum likelihood sequence estimation technique to a sequence of multi-dimensional values received over the channel; the encoder includes a finite state device whose next state depends upon at least an earlier state of the device; there are a plurality of subsets of the two-dimensional signal points and the minimum squared distance in two-dimensional space between signal points from the same subset is greater than the minimum squared distance between any two signal points; each group comprises two symbols and the multi-dimensional point alphabet is four-dimensional; the finite state device has eight states; each symbol has 7 bits and there are 240 distinct two-dimensional signal points; the modulation system is a double side band—quadrature carrier system; there are four subsets of signal points; and there is circuitry for effecting 180 differential encoding of said symbols.

The system achieves a coding gain with a redundancy (in the preferred embodiments) of less than one bit per symbol interval.

Other advantages and features will be apparent from the following description of the preferred embodiment, and from the claims.

DESCRIPTION OF THE PREFERRED EMBODIMENT

We first briefly describe the drawings.

Drawings

FIG. 1 is a block diagram of a data transmitter;

FIG. 2 is a diagram of representative signal points on a signal point constellation;

FIG. 3 is a block diagram of the signal selection logic of FIG. 1;

FIG. 4 is a block diagram of the convolution encoder of FIG. 3;

FIG. 5 is a diagram of a portion of a state-transition trellis showing representative transitions between states;

FIG. 6 is a table of state transitions for the trellis of FIG. 5;

FIG. 7 is a block diagram of a data receiver;

FIG. 8 is a block diagram of the decoder of FIG. 7;
FIG. 9 is a table of contending metric calculations;
FIG. 10 is a table of surviving metric calculations;
FIG. 11 is a table of minimum weight code sequences;
FIG. 12 is a block diagram of the differential encoder of FIG. 3.

STRUCTURE AND OPERATION

Referring to FIG. 1, in transmitter 10 (a programmed microprocessor) an input bit stream 12 (appearing at a bit rate of, for example, 19,200 bits per second) is made up of a sequence of digital symbols each having the same number of bits (N). The symbols are taken two at a time by serial/parallel converter 14 to form groups 16 each having two symbols. N is selected (e.g. N=7) so that the number of bits (2N) in each group 16 is an integer. (But N need not be integral.) Each two-symbol group 16 is encoded by signal selection logic 18 into a pair of two-dimensional signals 20, which are used successively by modulator 22 for conventional DSB-QC modulation and transmission over channel 24 at a rate of 2400×8/7 baud, corresponding to 7 bits per modulation interval.

The encoding process can be viewed as first selecting for each two-symbol group 16 a single four-dimensional point (i.e., a multi-dimensional point of more than two dimensions) from an available alphabet of four-dimensional points in four-dimensional space (called 4-space), and then using the four coordinate values of the selected multi-dimensional point to specify the two pairs of coordinates of the two two-dimensional signal points.

Referring to FIG. 2, each signal is drawn from a two-dimensional constellation 30 having 240 signal points 31 (i.e., more than the $2^N=128$ signal points required in an uncoded system but fewer than $2^{N+1}=256$ signal points). Each signal point 31 has odd integral coordinate values. All signal points 31 are grouped into four different subsets, respectively denoted (00), (01), (10), and (11), where for each subset the two bits in parentheses are respectively the least significant bits of the binary values of a and b taken from the following expression for the x and y coordinates of the signal:

$$(x, y)=(1+2a, 1+2b)$$

For example, signal point q has coordinates (x, y)=(11, 5), so that a=5=binary 101, b=2=binary 10. Thus, the least significant bits of a and b are a=1 and b=0, and signal point q is therefore in subset (10).

The complex signal plane can be viewed as being divided into 60 contiguous square sectors 32 each containing four signal points, one from each subset. Each quadrant of the plane contains 15 sectors, each identified by a value A_n (n an integer between 1 and 15) where n generally reflects the relative distance of a sector from the origin (e.g., sector A_{15} is farther from the origin than sector A_8).

The multi-dimensional points of the four-dimensional point alphabet similarly are categorized into 16 different multi-dimensional point subsets, each corresponding to a different combination of two signal point subsets. The multi-dimensional point subsets are respectively denoted (0000), (0001) . . . , the first two and final two bits of the value in parentheses being respectively the designations of the two signal point subsets to which the multi-dimensional point subset corresponds. For example, multi-dimensional point subset 0001 corresponds to signal point subsets (00) and (01).

Signal selection logic 18 is arranged to map each incoming two-symbol group comprising 14 bits (i_1–i_{14}) into a multi-dimensional point which is then converted to two signals points.

Referring to FIG. 3, signal selection logic 18 includes convolutional encoder 40, amplitude coder 42, differential encoder 43, and multi-dimensional-point-to-signal-pair converter 39.

Convolutional encoder 40 takes incoming bits i_1–i_3 (after manipulation in differential encoder 43) and adds a fourth redundancy bit, p, to give two two-bit values (called SET values) which correspond to the a and b values of the two different subsets from which the two signals are selected. The encoder thus introduces less than one bit per symbol of redundancy into the system, preferably no more than ½ bit per symbol. Bits i_4–i_7 are passed (after manipulation in differential encoder 43) through to become the four bits constituting the two values (called QUAD values) for identifying the quadrants from which the two signals are selected. Amplitude coder 42 takes bits i_8–i_{14} and generates 2 values (called A values) which correspond to the sectors from which the two signals are selected.

The two SET values, two QUAD values, and two A values can be viewed as together specifying one of the 32,768 (i.e., 2^{15}, where 15 is the number of bits (14) in the symbol group plus the one bit (p) added by encoder 40) possible multi-dimensional points in 4-space, which is then converted by converter 39 to a corresponding pair of signals. The 32,768 multi-dimensional points in the multi-dimensional point alphabet comprise those of the 57,600 four-dimensional points (each corresponding to a possible pair of two-dimensional signal points) which are closest to the origin in 4-space (i.e., require the least energy to send).

Referring to FIG. 4, convolutional encoder 40 includes four modulo 2 adders 43, 44, 46, 48, each connected to receive at least two of the three bits i_1–i_3 and three delay (memory) elements 50, 52, 54 (each having a delay of two symbol intervals) connected to adders 42, 44, 46, 48 as shown. Encoder 40 generates the additional bit (p) in each group interval (where a group interval is two symbol intervals corresponding to a two-symbol group) based on the values of bits i_1, i_2, i_3 in the corresponding two-symbol group, and also based on the values of some of the bits i_1, i_2, i_3 in two-symbol groups which appeared in prior group intervals. Bits i_1 and i_2 become the SET value for the signal sent in the first symbol interval of each group interval, and bits i_3 and p become the SET value for the signal sent in the second symbol interval. Thus, the convolutional encoder implements a rate ¾ code which adds ½ bit per modulation interval.

The memory elements 50, 52, 54 of convolutional encoder 40 effectively consist of a finite state device having eight possible states each represented by a three-bit value $s_1s_2s_3$ (where s_1, s_2, and s_3 are the respective states of elements 50, 52, 54) and each determined by the historical sequence of input bits i_1, i_2, and i_3. The convolutional encoder in this way assures that the multi-dimensional point subset from which each multi-dimensional point is drawn depends on the multi-dimensional point subsets from which previous multi-dimensional points were drawn, and therefore carries historical information (by means of the ½ bit per symbol of redun-

dancy) about the multi-dimensional point subsets of the preceding multi-dimensional points.

Encoder **40** is a finite state device which passes through a succession of states, the present state being separated in time from the previous state and also from the next state by a group interval.

For a given present state, only four of the eight next states are permissible. The other four of the eight next states are inherently impossible given the encoder's logic circuitry. Which next state occurs depends on the given present state and on which one of the eight possible combinations of $i_1i_2i_3$ bits is found in the current two-symbol group to be sent. For example, if the present state is **000** and the $i_1i_2i_3$ combination for the next two-symbol group is **000**, the next state must be **000**. In such a case, the two-symbol group is said to cause a transition from present state **000** to next state **000**.

Referring to FIG. **5**, a trellis **70** can be used to diagram all permissible transitions between present encoder states and next encoder states. The eight possible present states of encoder **40** are identified by a column of eight points (labeled (**000**), (**001**) . . .) where the three bits in parentheses are the bits s_1, s_2, s_3, representing the respective states of elements **50**, **52**, **54** in encoder **40**. The possible next states (which occur one group interval later) are similarly labeled ((**000**), (**001**) . . .).

The branches which connect the present states to the next states reflect the permissible state transitions. Each branch is labeled with four bits (e.g., **1111**) the first three of which indicate the bits (i_1, i_2, i_3) of the current two-symbol group to be encoded, and the fourth of which indicates the p bit added by the encoder. Together the four bits labeling a given branch thus correspond to one multi-dimensional point subset.

There is a pair of branches leading from a particular present state to a permissible next state. The two branches in each pair correspond to multi-dimensional points whose multi-dimensional point subset bits are binary complements. For example, the only permissible transitions between state **000** and state **011** are represented by a pair of branches corresponding to type **0110** and type **1001** multi-dimensional points (**0110** and **1001** being binary complements).

Referring to FIG. **6**, there are a total of 64 possible transitions (corresponding to trellis branches) between the present states and the permissible next states. Only eight of the 64 possible transitions are shown in FIG. **5**, namely those leading from present state **000**.

Referring again to FIG. **5**, the trellis represents a succession of permissible states spaced apart by group intervals and connected by permissible transitions. Only the states at two points in time are shown in FIG. **5** but the trellis is easily expanded to the left and right by simply repeating the columns of states and the pattern of permissible transitions.

Every permissible sequence of encoder states corresponds to a permissible path along a series of branches through the trellis. Every path in turn corresponds to a sequence of multi-dimensional point subsets corresponding to the branches which make up the path. Thus, in effect, the sequence of multi-dimensional point sent by the transmitter carries with it (in the form of the subsets of the multi-dimensional points sent) information about the encoder's path through the trellis.

As will be seen below, the receiver uses the received multi-dimensional values each corresponding to a pair of the received two-dimensional signals to estimate the encoder's original path through the trellis. Once the path is determined, the multi-dimensional points sent and hence the stream of symbols sent can be reconstructed.

Referring to FIG. **7**, in receiver **100** (a programmed microprocessor), the noise affected modulated carrier received from channel **24** is passed through demodulator **102** and signal processor **104** to produce a stream of received two-dimensional signals. Decoder **106** considers the stream of received two-dimensional signals as a stream of received multi-dimensional values and decides which multi-dimensional points (and hence which symbols) were sent by means of a so-called maximum likelihood sequence estimation technique using the Viterbi algorithm discussed in the Forney article.

In general, the decoding process involves first determining which path through the trellis is most likely to have been the one followed by the encoder. Once that maximum likelihood path is found, the sequence of multi-dimensional point subsets corresponding to that path (called the maximum likelihood path history) is used together with the sequence of received multi-dimensional values to decide which multi-dimensional points were sent from among the multi-dimensional point subsets representing the maximum likelihood path history.

The maximum likelihood path is determined by finding which permissible sequence of multi-dimensional point subsets (i.e., which trellis path) is closest (measured in aggregate squared distance in 4-space) to the sequence of received multi-dimensional values. The distance (called a branch metric) between a received multi-dimensional value and a permissible multi-dimensional point from a subset corresponding to a branch of the trellis is simply the squared distance between them in 4-space. The distance (called a path metric) between a received multi-dimensional value sequence and a permissible sequence of multi-dimensional points from subsets corresponding to a permissible trellis path is simply the arithmetic sum of the squared distances between each of the received multi-dimensional values in the sequence and the corresponding multi-dimensional points along the path.

The decoding process steps are repeated in each group interval. Because the decoding depends on analysis of a sequence of received multi-dimensional values, the decision of which multi-dimensional point was sent in a particular interval must be delayed for a number of group intervals until the probability of error in estimating the most likely trellis path is acceptably small.

For a given group interval, the first decoding step is to find the one multi-dimensional point in each subset which is closest to the received multi-dimensional value. This step alone reduces from 32,768 to 16 the number of contending multi-dimensional points for that interval.

Referring to FIG. **8**, this is done by passing the received multi-dimensional value through slicer **108** which performs two conventional slicing operations on the multi-dimensional point alphabet in each of four dimensions in the vicinity of the received multi-dimensional value.

Next, in branch metric calculator **110**, the squared distance between each received multi-dimensional value and each of the sixteen contending multi-dimensional points is computed. These squared distances are denoted d^2(**0000**), d^2(**0001**) . . . where the value in parentheses indicates the multi-dimensional point subset. For example, the value d^2(**0000**) is the squared distance

between the received multi-dimensional value and the contending multi-dimensional point in the **0000** subset.

Recalling that each present state and each corresponding permissible next state in the trellis are connected by a pair of branches corresponding to two different subsets of multi-dimensional points, and that there is only one most likely path through the trellis, only one branch of each pair of branches can lie on the maximum likelihood path. Thus, it is possible at this stage to reduce by half the number of contending branches simply by determining which branch of each pair represents the multi-dimensional point subset which is closer to the received multi-dimensional value.

To do this, branch metric calculator **110** determines as a so-called branch pair metric for each branch pair, denoted, e.g., b(**000**), the smaller of the previously determined branch metrics corresponding to the two branches in the pair. For example $b(000)=\min[d^2(0000), d^2(1111)]$, $b(001)=\min[d^2(0001), d^2(1110)]$ . . .

The next step (performed by contending metric calculator **112**) is to take the branch pair metric leading from each present state and add it to a so-called normalized surviving metric of that present state (determined in the manner described below) to obtain a so-called contending metric.

Referring to FIG. **9**, the eight surviving metrics are denoted **m(000), m(001)** . . . where the value in parentheses denotes a present state. The 32 contending metrics are denoted **m(000,000), m(000,001)**. . . where the values in parentheses denote a present state and a permissible next state.

There are four contending branches leading into each next state but only one can be in contention against the contending branches leading into the other next states, namely the one whose branch pair metric combined with the surviving metric of the present state from which the branch leads, produces the smallest contending metric.

Referring to FIG. **10**, the smallest contending metric for each next state is determined by simple comparisons, each yielding a surviving metric denoted, e.g. , **m(000)**, where the value in parentheses corresponds to the new state.

Of the eight surviving branches to the eight next states, only one is part of the maximum likelihood path, namely the one for which the surviving metric has the minimum value.

This minimum surviving metric (m(min)) is found (by minimum metric calculator **116**, FIG. **8**) from among the eight surviving metrics, i.e., m(min)=min[**m(000), m(001), m(010), m(011), m(100), m(101), m(110), m(111)**].

Finally, the minimum metric is subtracted from each of the normalized surviving metrics (by normalized surviving metric calculator **118**, FIG. **8**) to prevent the normalized surviving metrics from growing without bound.

This minimum surviving metric for the next group interval thus represents the minimum path metric through the trellis corresponding to the historical sequence of received multi-dimensional values. The decoder has thus determined the maximum likelihood path of the encoder through the trellis.

The next step is to determine the corresponding sequence of sent multi-dimensional points. For each of the eight possible present states, decoder **106** stores a so-called present surviving path history identifying the sequence of multi-dimensional points which correspond to the surviving path leading to each present state. When the eight surviving metrics for the eight possible next states are calculated, the decoder creates a next surviving path history for each next state. Each next surviving path history contains the multi-dimensional point corresponding to the surviving metric leading to each next state plus the sequence of past multi-dimensional points of the corresponding present surviving path history.

The next surviving path history which corresponds to the minimum surviving metric contains the sequence of multi-dimensional points which is the best estimate at that time of the sequence of multi-dimensional points sent.

In a given surviving path history the multi-dimensional points which are many group intervals old are more likely to be correct than more recent multi-dimensional points. The decision of which multi-dimensional point was sent in a given group interval is made after the passage of a predetermined number of group intervals (e.g., 16) selected such that the probability of error is acceptably low.

The coding gain produced by the described coding system depends on the error probability and on the average energy required to send the two-dimensional signal points.

The error probability can be determined by first considering the output of the encoder as a bit stream

$$i_1^{(1)} i_2^{(1)} i_3^{(1)} p^{(1)} i_1^{(2)} i_2^{(2)} i_3^{(2)} p^{(2)} \ldots i_1^{(N)} i_2^{(N)} i_3^{(N)} p^{(n)}$$

where, e.g., $i_2^{(2)}$ is the value of output bit i_2 for the second group interval. It is then possible to determine as a so-called impulse response the string of those output bits of encoder **40** which will have "1" values (as determined by the logic of encoder **40**) when a single predetermined input bit has a "1" value. For example, the impulse response resulting from only bit i_1 having a "1" value for the first group interval can be represented by the impulse response

$$i_1^{(1)} p^{(1)} p^{(2)} p^{(3)}$$

meaning that $i_1^{(1)}=p^{(1)}=p^{(2)}=p^{(3)}=1$. Similarly the impulse responses respectively resulting from $i_2^{(1)}=1$ and $i_3^{(1)}=1$, are

$$i_2^{(1)} p^{(1)} p^{(3)} p^{(4)}$$

$$i_3^{(1)} p^{(1)} p^{(2)} p^{(4)}$$

All other possible bit sequences (called code sequences) are shifts and linear (mod 2) combinations of the three impulse responses.

The difference (mod 2 sum) between any two code sequences is another code sequence, and therefore, the minimum Hamming distance between any two code sequences generated by encoder **40** is the minimum number of 1 values (called the minimum weight) in a non-zero code sequence. Because the impulse responses each have weight 4, which is even, the minimum Hamming distance must be either 2 or 4. However, no linear combination of the impulse responses has weight 2, so the minimum distance must be 4.

Referring to FIG. **11**, there are 22 distinct minimum weight code sequences.

Thus, the minimum noise energy required to cause an error in decoding is $4d_0^2$, where $2d_0$ is the minimum distance between any two two-dimensional signal points (i.e., d_0 is the distance from a two-dimensional signal point to the nearest decision boundary in two-dimensional space.) Such an error could occur in the direction of any of the 22 distinct minimum weight code sequences of FIG. **11**, in each case in any of sixteen ways per group interval. In addition, the $4d_0^2$ noise energy could cause an error between neighboring multi-dimensional points in a single subset in any one of eight different ways in each group interval. Thus, the union bound of error probability per group interval is 22 times 16 plus 8 equals $360Q(2d_0)$. Simulations suggest that this union bound is conservative by a factor of 2 so that the error probability per symbol interval is approximately $90Q(2d_0)$ compared with $4Q(d_0)$ for an uncoded system.

Using the rule of thumb that in the error rate region of interest, every factor of 2 in increased error rate corresponds to a cost of 0.2 db in signal-to-noise ratio, the error coefficient penalty for the described coding system is 0.9 db compared with an uncoded system.

The $4d_0^2$ minimum noise energy for the coded system gives a 6 db gross coding gain over uncoded systems (which have a d_0^2 minimum noise energy), which is offset not only by the 0.9 db loss from increased error probability, but also by the additional 1.5 db needed to send the extra bit (p) per group interval which the encoder adds to the original 14 bits of each two-symbol group. Thus, the net coding gain is 6 db−1.5 db−0.9 db=3.6 db.

Referring to FIG. **12**, differential encoder **43** includes modulo 2 summers **120, 122, 124, 126, 128, 130, 132,** and delay element **134** (representing a one group interval delay) which together convert incoming bits i_1 through i_7 to differentially encoded bits $\bar{i}_1$ through $\bar{i}_7$. Bits $\bar{i}_1$ and $\bar{i}_2$ are the SET bits for the first symbol interval in each group interval. Bit $\bar{i}_3$, together with bit p are the SET bits for the second symbol interval. Bits $\bar{i}_4$, $\bar{i}_5$ and $\bar{i}_6$, $\bar{i}_7$ are respectively the QUAD bits for the first and second symbol intervals. (The assignments of QUAD bits to quadrants are shown on FIG. **2**.)

The differential encoder effectively complements the SET and QUAD bits of the signal point to be sent if the previous signal point was in the bottom half-plane (i.e., had 1 as its first QUAD bit). The complementing is accomplished by delivering the output of delay element **134** to summers **124, 126, 130, 132**. Because $i_1i_2i_3$ are complemented, the parity bit (p) is also complemented. The A bits remain unchanged so the pair of resulting signal points is 180° out of phase with the pair that would have been generated had $\bar{i}_6$ been 0 in the previous group interval.

At the receiver, the reverse process is performed at the output of decoder **106**, ensuring that a 180° phase reversal on the channel will cause only a momentary error in the decoded symbols.

Other embodiments are within the following claims.

I claim:

1. In a modulation system for sending digital symbols generated by a data source over a band-limited channel in accordance with a sequence of multi-dimensional points each composed of a plurality of two-dimensional modulation signal points, and each selected from an available alphabet of said multi-dimensional points by an encoder on the basis of a group of said digital symbols, the improvement comprising

circuitry connected to be responsive to said data source for accumulating said symbols of each said group, and

circuitry connected to be responsive to said accumulating circuitry for thereafter selecting said multi-dimensional point for said group, and wherein

said available alphabet comprises a plurality of subsets of said multi-dimensional points, and

the subset from which the multi-dimensional point is selected for each said group depends on the subset from which the muti-dimensional point is selected for another said group.

2. In a modulation system for sending digital symbols generated by a data source over a band-limited channel in accordance with a sequence of multi-dimensional points each composed of a plurality of two-dimensional signal points, said modulation system comprising,

circuitry connected to be responsive to said data source for accumulating groups of said symbols,

selection circuitry connected to be responsive to said accumulating circuitry for selecting one said multi-dimensional point for each said group from an available alphabet of multi-dimensional points, and

modulator circuitry connected to be responsive to said selection circuitry for modulating a carrier in accordance with the signal points of which said slected multi-dimensional points are composed, at a rate of 1/T signal points per second,

the improvement wherein,

said available alphabet has a plurality of subsets of said multi-dimensional points, and

said selection circuitry comprises

means connected to be responsive to said accumulating circuitry for causing a multi-dimensional point for each said group to be selected from a subset which depends on the subset from which the multi-dimensional point is selected for another said group.

3. The improvement of claim **1** or **2** wherein said selection circuitry includes means responsive to said accumulating means for adding to the information carried by said symbols less than one bit per symbol interval of information about the dependencies among said selected multi-dimensional points.

4. The improvement of claim **3** wherein said accumulating circuitry is arranged to add no more than one-half bit per symbol interval.

5. The improvement of claim **1** or **2** further comprising a decoder connected to be responsive to said channel for deciding which said multi-dimensional points were sent by applying a maximum likelihood sequence estimation technique to a sequence of multi-dimensional values received over said channel.

6. The improvement of claim **1** or **2** wherein said selection circuitry comprises a finite state device connected to be responsive to said accumulating circuitry and whose next state depends upon at least an earlier state of said device.

7. The improvement of claim **1** or **2** wherein there are a plurality of subsets of said modulation signal points and the minimum squared distance in two-dimensional space between modulation signal points from the same subset is greater than the minimum squared distance between any two modulation signal points.

8. The improvement of claim **1** or **2** wherein each said group comprises an integral number of bits.

9. The improvement of claim 1 or 2 wherein each said group comprises two said symbols and said multi-dimensional point alphabet is four-dimensional.

10. The improvement of claim 6 wherein said finite state device has eight states.

11. The improvement of claim 10 wherein each symbol comprises 7 bits and there are 240 distinct two-dimensional signal points.

12. The improvement of claim 1 or 2 wherein said modulation system is a double side band—quadrature carrier system.

13. The improvement of claim 1 or 2 wherein there are four subsets of said modulation signal points.

14. The improvement of claim 1 or 2 further comprising circuitry for effecting 180° differential encoding of said symbols.

* * * * *

EXHIBIT F

US005214656A

United States Patent [19]
Chung et al.

[11] Patent Number: 5,214,656
[45] Date of Patent: May 25, 1993

[54] MULTIPLEXED CODED MODULATION WITH UNEQUAL ERROR PROTECTION

[75] Inventors: **Hong Y. Chung**, Eatontown; **Jin-Der Wang**, Ocean; **Lee-Fang Wei**, Lincroft, all of N.J.

[73] Assignee: **AT&T Bell Laboratories**, Murray Hill, N.J.

[21] Appl. No.: **627,156**

[22] Filed: **Dec. 13, 1990**

[51] Int. Cl.^{5} **G06F 11/00**
[52] U.S. Cl. **371/43**; 375/39
[58] Field of Search 371/37, 38, 43–46; 375/39, 58

[56] References Cited

PUBLICATIONS

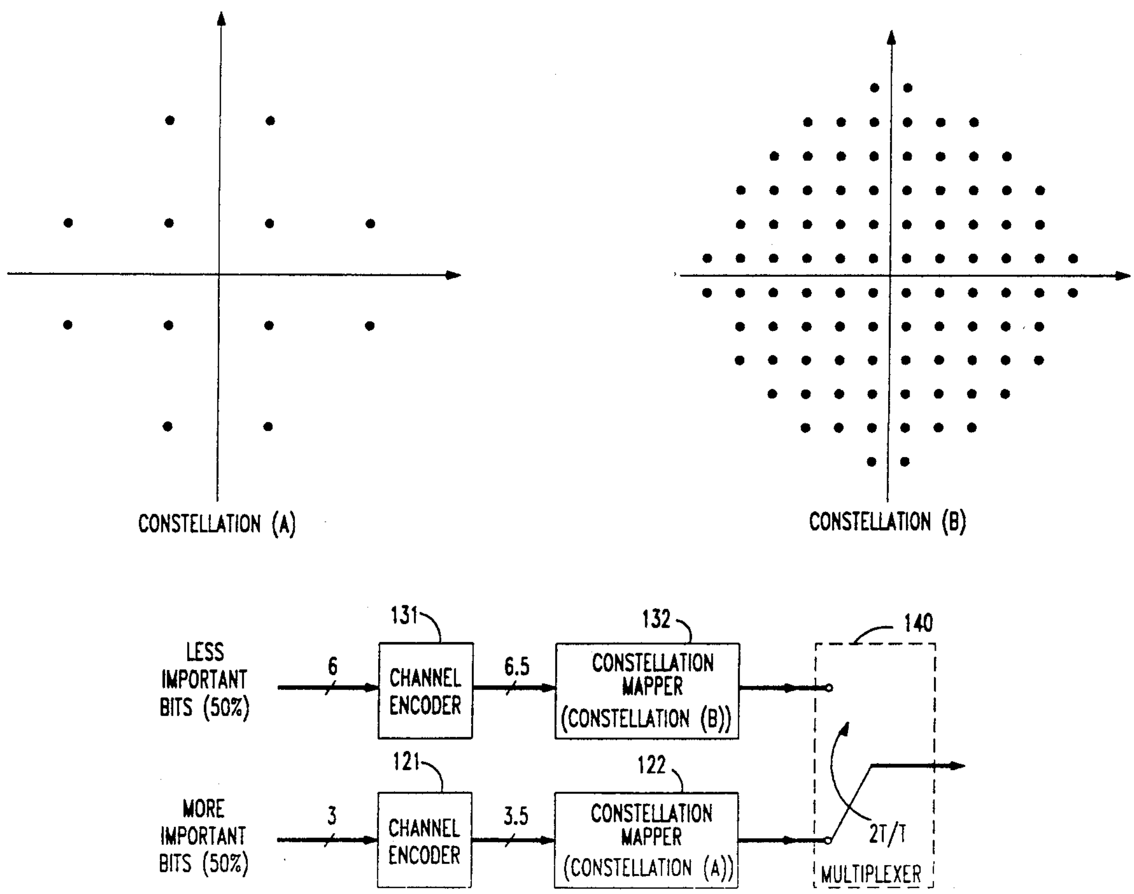
U.S. patent application Ser. No. 7/363,793, Wang et al., filed Jun. 9, 1989.

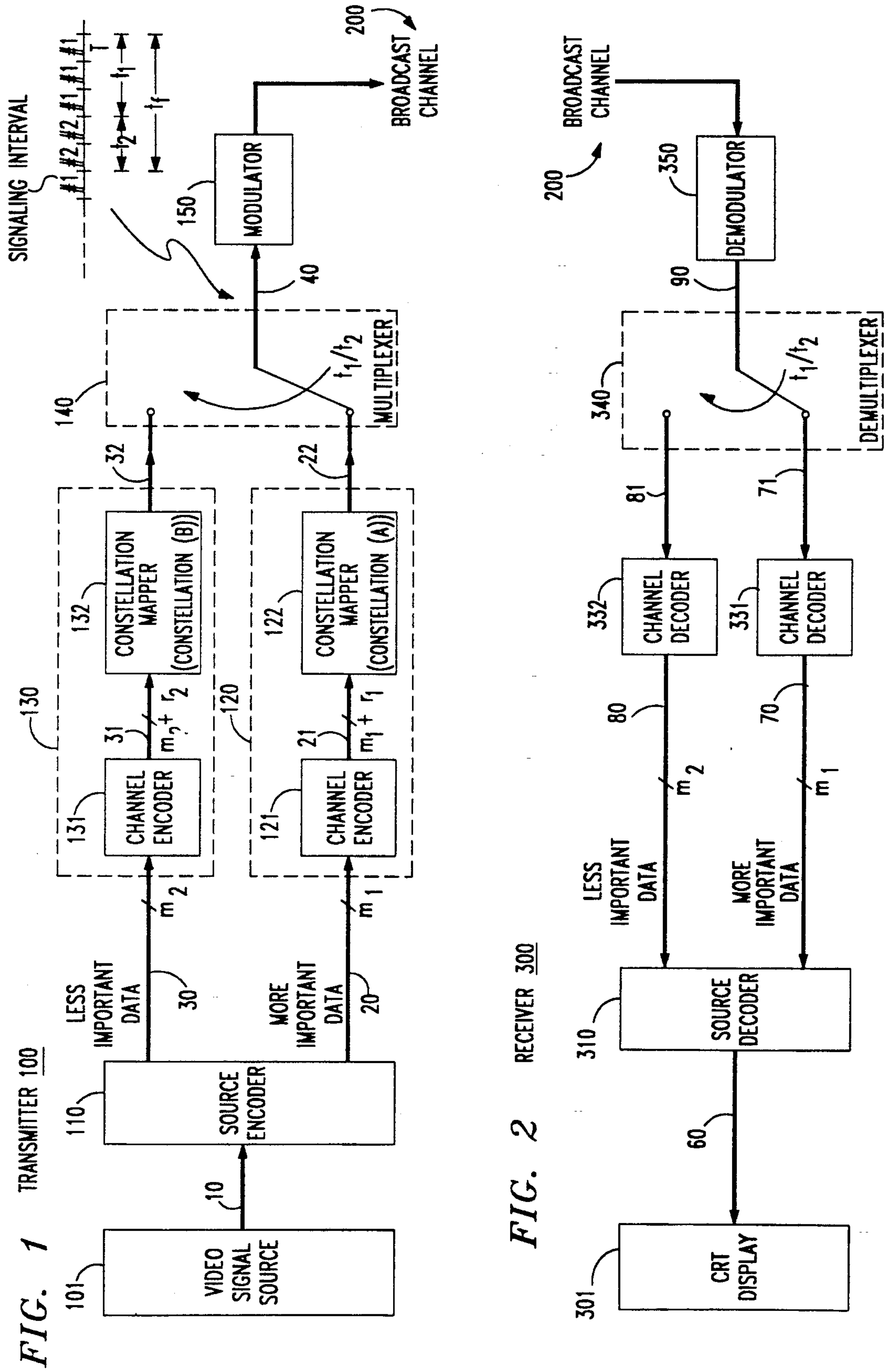
Primary Examiner—Vincent P. Canney
Attorney, Agent, or Firm—Henry T. Brendzel

[57] ABSTRACT

Unequal error protection is provided for an HDTV signal by separately coding each one of the classes of information in the HDTV signal by using a conventional coded modulation scheme and then time-division-multiplexing the various coded outputs for transmission. In particular, each class of information is separately coded by a 4-dimensional 8-state trellis code and a uniformly-spaced (QAM) signal constellation.

32 Claims, 7 Drawing Sheets





TRANSMITTER 100
VIDEO SIGNAL SOURCE
101
10
SOURCE ENCODER
110
LESS IMPORTANT DATA
30
MORE IMPORTANT DATA
20
m_2
m_1
CHANNEL ENCODER
131
CHANNEL ENCODER
121
31
$m_2 + r_2$
21
$m_1 + r_1$
130
120
CONSTELLATION MAPPER (CONSTELLATION (B))
132
CONSTELLATION MAPPER (CONSTELLATION (A))
122
32
22
140
MULTIPLEXER
t_1/t_2
40
MODULATOR
150
BROADCAST CHANNEL
200
SIGNALING INTERVAL
#1 #2 #2 #1 #1 #1
T
t_2
t_1
t_f
RECEIVER 300
BROADCAST CHANNEL
200
DEMODULATOR
350
90
DEMULTIPLEXER
340
t_1/t_2
81
71
CHANNEL DECODER
332
CHANNEL DECODER
331
80
70
m_2
m_1
LESS IMPORTANT DATA
MORE IMPORTANT DATA
SOURCE DECODER
310
60
CRT DISPLAY
301

FIG. 1

FIG. 2

FIG. 3

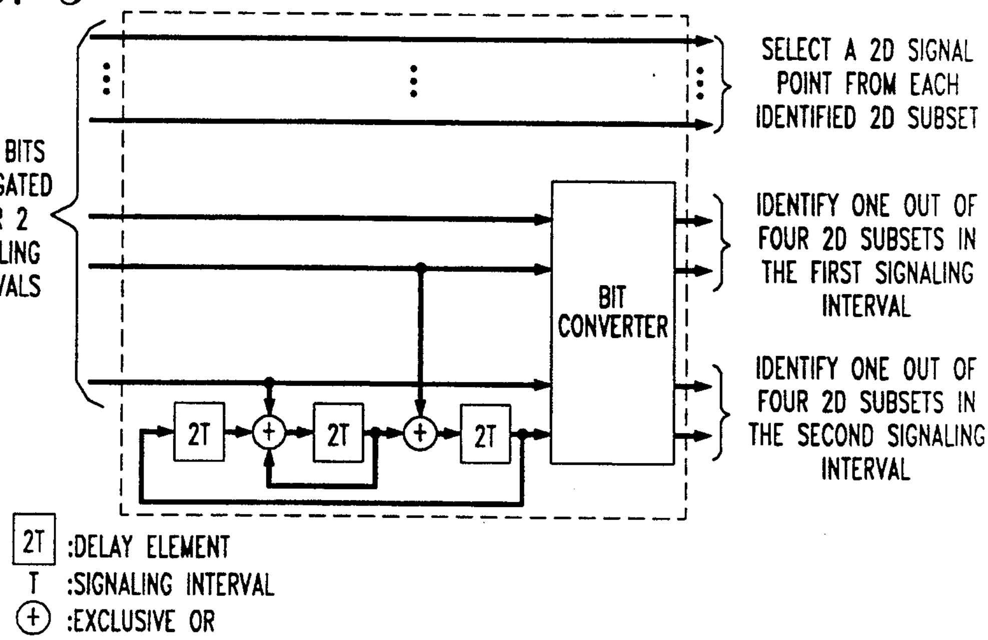


FIG. 4

BIT CONVERTER IN FIG. 3	
INPUT BIT PATTERN*	OUTPUT BIT PATTERN*
0 0 0 0	0 0 0 0
0 0 0 1	0 0 0 1
0 0 1 0	0 0 1 1
0 0 1 1	0 0 1 0
0 1 0 0	0 1 0 1
0 1 0 1	0 1 1 1
0 1 1 0	0 1 1 0
0 1 1 1	0 1 0 0
1 0 0 0	1 1 1 1
1 0 0 1	1 1 1 0
1 0 1 0	1 1 0 0
1 0 1 1	1 1 0 1
1 1 0 0	1 0 1 0
1 1 0 1	1 0 0 0
1 1 1 0	1 0 0 1
1 1 1 1	1 0 1 1

*READING FROM TOP TO BOTTOM IN FIG. 3

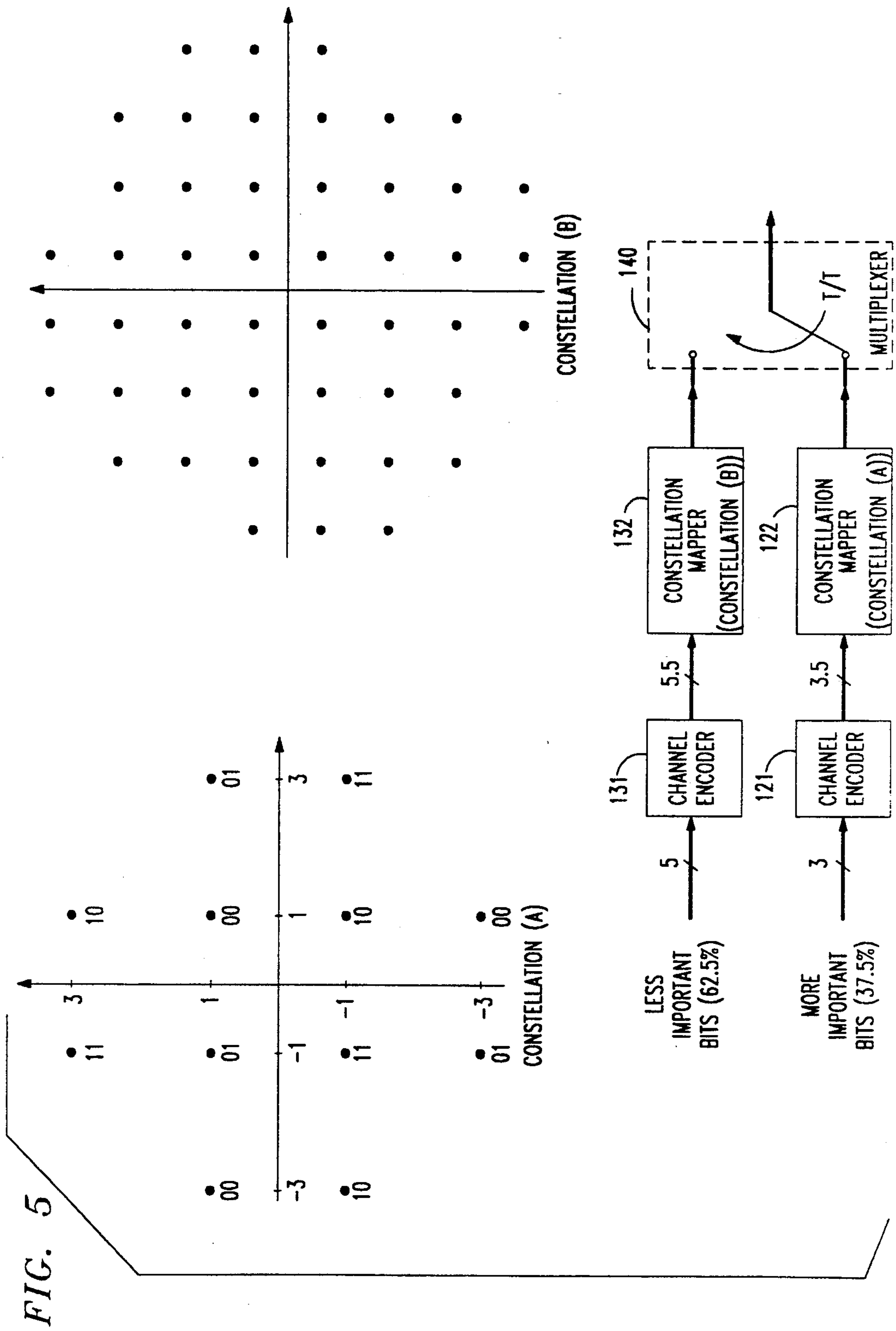

CONSTELLATION (B)
CONSTELLATION (A)
11
10
01
00
3
1
-1
-3
140
T/T
MULTIPLEXER
132
CONSTELLATION MAPPER (CONSTELLATION (B))
122
CONSTELLATION MAPPER (CONSTELLATION (A))
5.5
3.5
131
CHANNEL ENCODER
121
CHANNEL ENCODER
5
3
LESS IMPORTANT BITS (62.5%)
MORE IMPORTANT BITS (37.5%)

FIG. 5

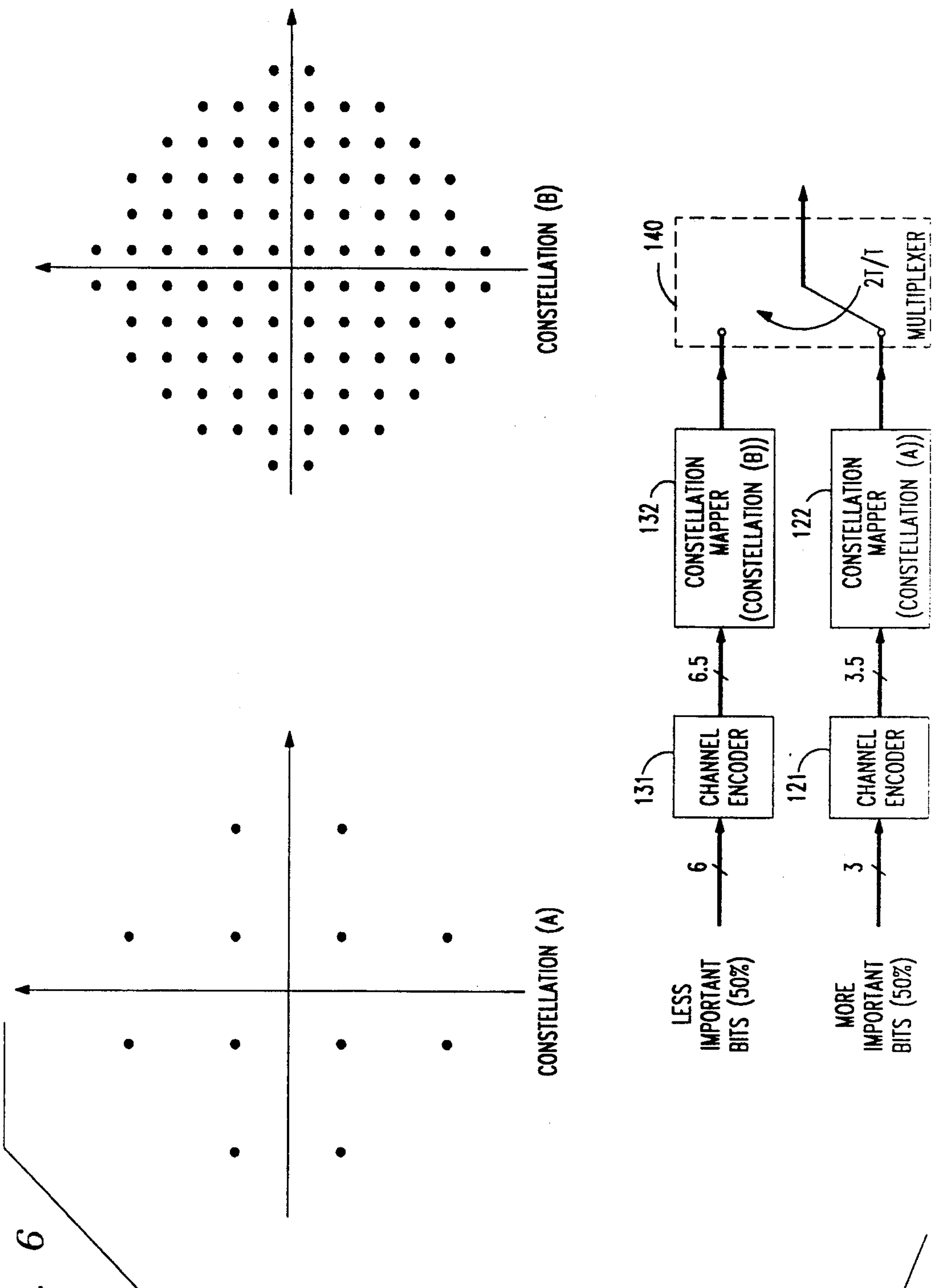
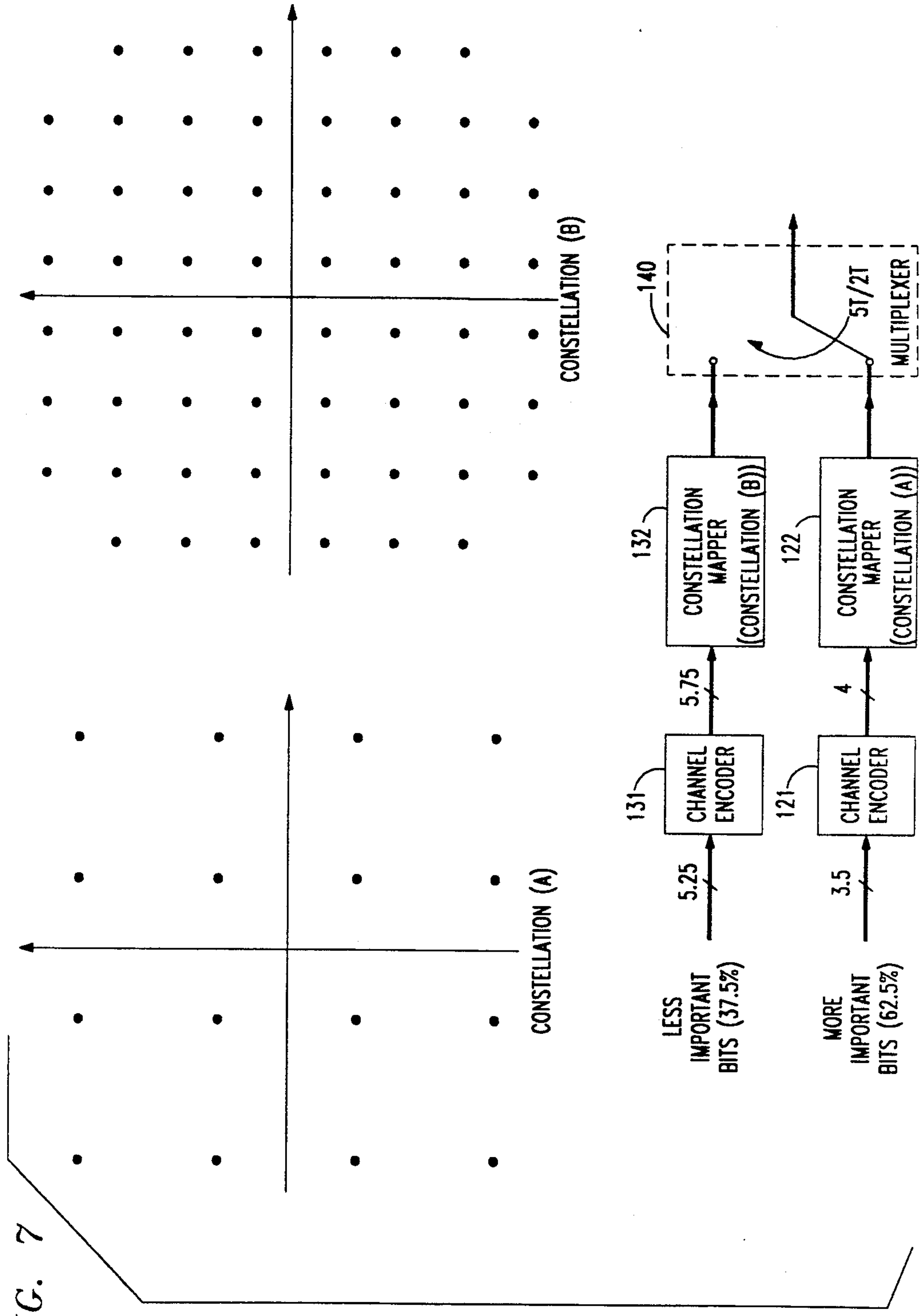

CONSTELLATION (B)
CONSTELLATION (A)
140
MULTIPLEXER
2T/T
132
CONSTELLATION MAPPER (CONSTELLATION (B))
122
CONSTELLATION MAPPER (CONSTELLATION (A))
6.5
3.5
131
CHANNEL ENCODER
121
CHANNEL ENCODER
6
3
LESS IMPORTANT BITS (50%)
MORE IMPORTANT BITS (50%)

FIG. 6



CONSTELLATION (B)
CONSTELLATION (A)
140
5T/2T
MULTIPLEXER
132
CONSTELLATION MAPPER (CONSTELLATION (B))
122
CONSTELLATION MAPPER (CONSTELLATION (A))
5.75
4
131
CHANNEL ENCODER
121
CHANNEL ENCODER
5.25
3.5
LESS IMPORTANT BITS (37.5%)
MORE IMPORTANT BITS (62.5%)

FIG. 7

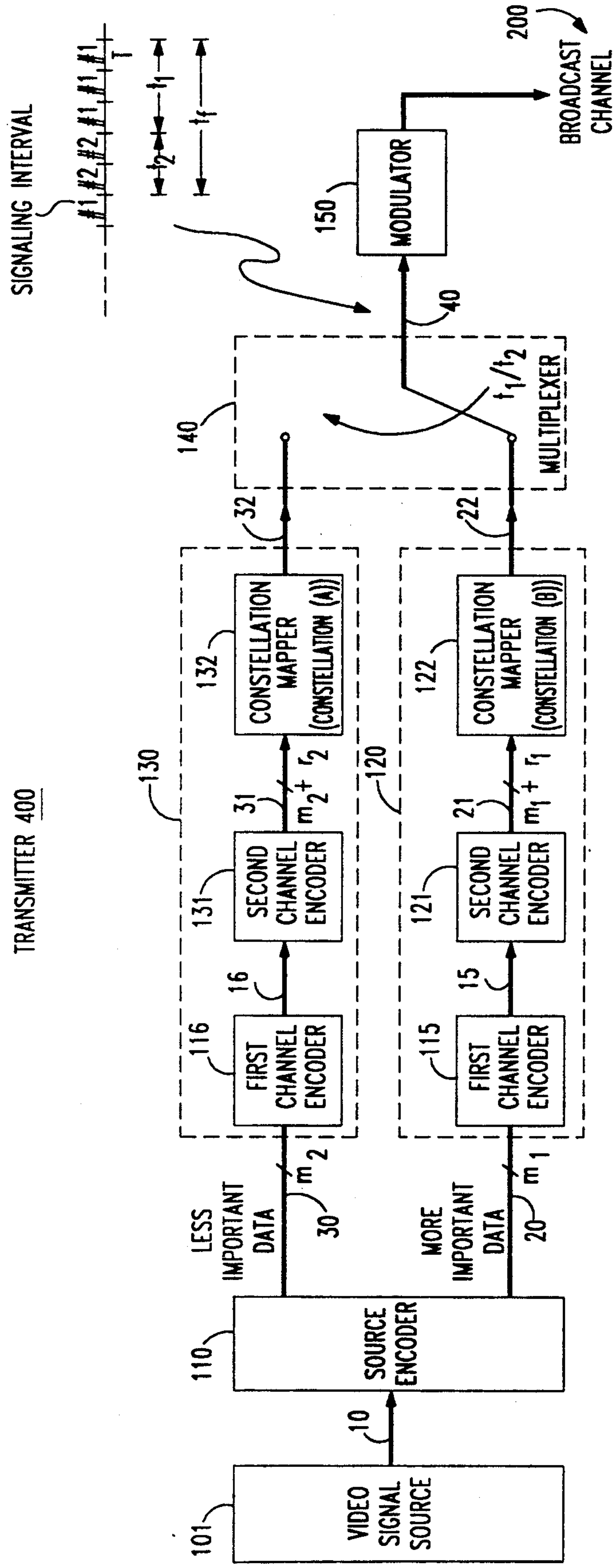
FIG. 8

COMPARISONS OF MULTIPLEXED CODED MODULTATION

SCHEME	PERCENTAGE OF IMPORTANT DATA (%)	MORE IMPORTANT DATA			LESS IMPORTANT DATA			t_1/t_2 OF MULTIPLEXER	PEAK-TO-AVERAGE POWER RATIO
		m_1	CONSTELLATION (A)	NOMINAL CODING GAIN (dB)**	m_2	CONSTELLATION (B)	NOMINAL CODING GAIN (dB)**		
1	37.5	3	12-QAM	7.6	5	48-QAM	1.5	T/T	2.07
3	50	3	12-QAM	7.6	6	96-QAM	-1.5	2T/T	2.17
4	62.5	3.5	16-QAM	6.0	5.25	60-QAM	0.8	5T/2T	2.24

** RELATIVE TO UNCODED 16-QAM

FIG. 9


TRANSMITTER 400
SIGNALING INTERVAL
#1 #2 #2 #1 #1 #1 #1
T
t_2
t_1
t_f
101
VIDEO SIGNAL SOURCE
10
110
SOURCE ENCODER
LESS IMPORTANT DATA
30
m_2
MORE IMPORTANT DATA
20
m_1
130
116
FIRST CHANNEL ENCODER
16
131
SECOND CHANNEL ENCODER
31
$m_2 + r_2$
132
CONSTELLATION MAPPER (CONSTELLATION (A))
32
120
115
FIRST CHANNEL ENCODER
15
121
SECOND CHANNEL ENCODER
21
$m_1 + r_1$
122
CONSTELLATION MAPPER (CONSTELLATION (B))
22
140
t_1/t_2
MULTIPLEXER
40
150
MODULATOR
200
BROADCAST CHANNEL

MULTIPLEXED CODED MODULATION WITH UNEQUAL ERROR PROTECTION

BACKGROUND OF THE INVENTION

The present invention relates to the transmission of digital data, particularly the transmission of digital data which represents video signals.

It is generally acknowledged that some form of digital transmission will be required for the next generation of television (TV) technology, conventionally referred to as high definition television, or HDTV. This requirement is due mostly to the fact that much more powerful video compression schemes can be implemented with digital signal processing than with analog signal processing. However, there has been some concern about becoming committed to an all-digital transmission system because of the potential sensitivity of digital transmission to small variations in signal-to-noise ratio, or SNR, at the various receiving locations.

This phenomenon—sometimes referred to as the "threshold effect"—can be illustrated by considering the case of two television receivers that are respectively located at 50 and 63 miles from a television broadcast station. Since the power of the broadcast signal varies roughly as the inverse square of the distance, it is easily verified that the difference in the amount of signal power received by the television receivers is about 2 dB. Assume, now, that a digital transmission scheme is used and that transmission to the receiver that is 50 miles distant exhibits a bit-error rate of 10^{-6}. If the 2 dB of additional signal loss for the other TV set translated into a 2 dB decrease of the SNR at the input of the receiver, then this receiver will operate with a bit-error rate of about 10^{-4}. With these kinds of bit-error rates, the TV set that is 50 miles away would have a very good reception, whereas reception for the other TV set would probably be very poor. This kind of quick degradation in performance over short distances is generally not considered acceptable by the broadcasting industry. (By comparison, the degradation in performance for presently used analog TV transmission schemes is much more graceful.)

There is thus required a digital transmission scheme adaptable for use in television applications which overcomes this problem. Solutions used in other digital transmission environments—such as the use of a) regenerative repeaters in cable-based transmission systems or b) fall-back data rates or conditioned telephone lines in voiceband data applications—are clearly inapplicable to the free-space broadcast environment of television.

The co-pending, commonly assigned United States patent application of V. B. Lawrence et al. entitled "Coding for Digital Transmission," Ser. No. 07/611,225, filed on Nov. 07, 1990, discloses a technique for overcoming the shortcomings of standard digital transmission for over-the-air broadcasting of digital TV signals. Specifically, the Lawrence et al. patent application teaches the notion of characterizing the HDTV signal into classes of "less important" and "more important" information which will then use a constellation of non-uniformly spaced signal points. This approach provides unequal error protection, i.e., more error protection for the more important information, and allows a graceful degradation in reception quality at the TV set location because, as the bit-error rate at the receiver begins to increase with increasing distance from the broadcast transmitter, it will be the bits that represent proportionately less of the TV signal information that will be the first to be affected.

SUMMARY OF THE INVENTION

Although the Lawrence et al. patent application teaches an advantageous technique for providing unequal error protection to a plurality of classes of information within a signal, we have discovered an alternative, and also advantageous, technique for providing unequal error protection. Specifically, and in accordance with the present invention, unequal error protection is provided for a signal comprised of a plurality of classes of information by a) separately coding each one of the plurality of classes of information using a different coded modulation scheme and b) multiplexing the plurality of coded outputs for transmission.

In accordance with a feature of the invention, uniformly spaced signal points can be used.

In a preferred embodiment of the invention, an HDTV signal is source-encoded to provide a plurality of classes of information. Each class of information is then separately coded by a different, and conventional, coded modulation scheme, e.g., a 4D 8-state trellis code and a uniformly-spaced QAM signal constellation. The coded outputs of the separate coded modulation schemes are then time-division-multiplexed for transmission of the HDTV signal.

BRIEF DESCRIPTION OF THE DRAWING

In the drawing,

FIG. 1 is a block diagram of an illustrative transmitter embodying the principles of the invention;

FIG. 2 is a block diagram of an illustrative receiver embodying the principles of the invention;

FIGS. 3-4 when taken together, show an illustrative trellis encoder used scheme using a 12-QAM signal constellation and a 48-QAM constellation in the transmitter of FIG. 1;

FIG. 5 shows an embodiment of a multiplexed coded modulation scheme using a 12-QAM signal constellation and a 48-QAM constellation in the transmitter of FIG. 1;

FIG. 6 shows an alternative embodiment of a multiplexed coded modulation scheme using a 12-QAM signal constellation and a 96-QAM constellation in the transmitter of FIG. 1;

FIG. 7 shows another alternative embodiment of a multiplexed coded modulation scheme using a 16-QAM signal constellation and a 60-QAM constellation in the transmitter of FIG. 1;

FIG. 8 shows a table comparing the nominal coding gains for the three embodiments of FIGS. 5-7; and

FIG. 9 is a block diagram of an illustrative transmitter embodying the principles of the invention using a concatenated coding technique.

DETAILED DESCRIPTION

Before proceeding with a description of the illustrative embodiment, it should be noted that the various digital signaling concepts described herein—with the exception, of course, of the inventive concept itself—are all well known in, for example, the digital radio and voiceband data transmission (modem) arts and thus need not be described in detail herein. These include such concepts as multidimensional signaling using 2N-dimensional channel symbol constellations, where N is some integer; trellis coding; fractional coding; scram-

bling; passband shaping; equalization; Viterbi, or maximum-likelihood, decoding; etc. These concepts are described in such United States patents as U.S. Pat. No. 3,810,021, issued May 7, 1974 to I. Kalet et al.; U.S. Pat. No. 4,015,222, issued Mar. 29, 1977 to J. Werner; U.S. Pat. No. 4,170,764, issued Oct. 9, 1979 to J. Salz et al.; U.S. Pat. No. 4,247,940, issued Jan. 27, 1981 to K. H. Mueller et al.; U.S. Pat. No. 4,304,962, issued Dec. 8, 1981 to R. D. Fracassi et al.; U.S. Pat. No. 4,457,004, issued Jun. 26, 1984 to A. Gersho et al.; U.S. Pat. No. 4,489,418, issued Dec. 18, 1984 to J. E. Mazo; U.S. Pat. No. 4,520,490, issued May 28, 1985 to L.-F. Wei; U.S. Pat. No. 4,597,090, issued Jun. 24, 1986 to G. D. Forney, Jr. and U.S. Pat. No. 4,941,154, issued Jul. 10, 1990 to L. -F. Wei. Additionally, reference can also be made to "Efficient modulation for band-limited signals", G. D. Forney, Jr. et al., *IEEE J. Select. Areas Commun.*, vol. SAC-2, pp. 632–647, September 1984; "Trellis-coded modulation with multidimensional constellations", L. -F. Wei, *IEEE Trans. Inform. Theory*, vol. IT-33, pp. 483–501, July 1987; and "Multidimensional constellations-Part I: Introduction, figures of merit, and generalized cross constellations," G. D. Forney, Jr. & L. -F. Wei, *IEEE J. Select. Areas Commun.*, vol. SAC-7, pp. 877–892, August 1989. All of the above are hereby incorporated by reference.

As previously mentioned, the co-pending, U.S. patent application of V. B. Lawrence et al., Ser. No. 07/611,225, filed on Nov. 7, 1990, discloses a technique for overcoming the shortcomings of standard digital transmission for over-the-air broadcasting of digital TV signals. Specifically, the Lawrence et al. patent application teaches the notion of characterizing the HDTV signal into classes of "less important" and "more important" information which will then use a constellation of non-uniformly spaced signal points. This approach provides unequal error protection, i.e., more protection for the more important information, and allows a graceful degradation in reception quality at the TV set location because, as the bit-error rate at the receiver begins to increase with increasing distance from the broadcast transmitter, it will be the bits that represent proportionately less of the TV signal information that will be the first to be affected. However, we have discovered an alternative, also advantageous, technique for providing unequal error protection. Specifically, and in accordance with the present invention, unequal error protection is provided for a signal comprised of a plurality of classes of information by a) separately coding each one of the plurality of classes of information using a different coded modulation scheme and b) multiplexing the plurality of coded outputs for transmission. Before proceeding with a description of three illustrative embodiments of the invention, the inventive concept itself will generally be described.

Turning, in particular, to FIG. **1**, information signal source **101** generates an HDTV analog video signal (HDTV signal) representing picture information. The HDTV signal is passed on to source encoder **110** which generates a digital signal comprised of a plurality of data elements which are grouped into "classes of information" in which at least one class of information is more important, i.e., contains "more important data", than the remainder of the classes of information which, therefore, contain "less important data". For example, the more important data represents that information which, if properly received, will form a rough picture, e.g., audio information, framing information, etc., and

the less important data represents that information which comprises the remainder of the HDTV signal. As represented herein, the more important data is generated on lead **20** and the less important data is generated on lead **30**. Illustratively, each data element is a data bit, with an average of m_1 (m_2) bits being generated on lead **20** (**30**) for each signaling interval assigned by multiplexer **140** to the more (less) important data (see below), each signaling interval having a duration of T seconds.

As shown in FIG. **1**, the more important data on lead **20** is input to channel encoder **121** of coded modulation circuitry **120**, and the less important data on lead **30** is input to channel encoder **131** of coded modulation circuitry **130**. Coded modulation circuitry **120** (**130**) represents a coded modulation scheme and is comprised of channel encoder **121** (**131**) and constellation mapper **122** (**132**). In accordance with a principle of the invention, the coded modulation schemes implemented by coded modulation circuitry **120** and **130** (described below) are chosen such that the more important data is provided more error protection than the less important data, i.e., coded modulation circuitry **120** and **130** are different, with channel encoders **121** and **131**, and/or constellation mappings **122** and **132** being different from each other. Channel encoder **121** (**131**) operates in accordance with known encoding techniques (described below), and the "encoded output" of channel encoder **121** (**131**) consists of m_1+r_1 (m_2+r_2) data bits, where r_1 (r_2) represents the average number of redundant bits introduced by the encoder **121** (**131**) in each signaling interval assigned by multiplexer **140** to the more (less) important data. The encoded output of channel encoder **121** (**131**) is mapped to a signal point from constellation A (B), for each assigned signaling interval, by constellation mapper **122** (**132**) to provide the "coded output" on leads **22** (**32**) to multiplexer **140**.

Multiplexer **140**, illustratively a time-division-multiplexer, is shown as a switch with a design parameter t_1/t_2, i.e., over a time frame $t_f=t_1+t_2$, multiplexer **140** will switch between coded modulation circuitry **120** and **130**. For example, during the time interval t_1 multiplexer **140** will provide the coded output from coded modulation circuitry **120** to modulator **150**, and during the time interval t_2 multiplexer **140** will provide the coded output from coded modulation circuitry **130** to modulator **150**. (It should be noted that although the simple case of only two classes of information is described herein, the concept can easily be extended to a larger plurality of classes.) Each time interval t_i, for $i=1,2$, is comprised of a number of signaling intervals, T, i.e., $t_1=N_1T$ and $t_2=N_2T$, where $N_1(N_2)$ is the number of signaling intervals in t_1 (t_2). In fact, the design parameter t_1/t_2 denotes the ratio of the numbers of signaling intervals assigned to the more important data and the less important data (i.e., the signaling intervals assigned to channel encoders **121** and **131**). For example, for each signaling interval in t_1 (t_2), channel encoder **121** (**131**) is mapped to a signal point from constellation A (B) so that over the time interval t_1 (t_2) the coded output of coded modulation circuitry **120** (**130**) will be comprised of N_1 (N_2) signal points. Therefore, and in accordance with the principles of the present invention, by allocating separate time intervals to the more important data and the less important data in a time frame, t_f, the more important data can be separately and differently coded from the less important data. Further, by changing the ratio of t_1/t_2, additional flexibility can be achieved in the design of the separate

coding schemes to provide further error protection for the more important data at the expense of the less important data. For example, by increasing the duration of t_1 relative to t_2, the size of the signal constellation used by constellation mapper **122** can be smaller, i.e. the signal points can be spaced further apart, however, this will result in t_2 being smaller, which will require constellation mapper **132** to use a larger constellation of signal points, i.e., the signal points which will be closer together. As a result, since the distance between signal points in a constellation has an effect on the amount of error protection provided by a coded modulation scheme, the error protection of the more important data is enhanced as the expense of the less important data. Coded modulation circuitry **120** and **130**, and multiplexer **140** are illustrative of an implementation of a "multiplexed coded modulation scheme". The bandwidth efficiency of the multiplexed coded modulation scheme of FIG. **1** is given by $(m_1t_1+m_2t_2)/(t_1+t_2)$ data bits per signaling interval, with the fraction of more important data being $(m_1t_1)/(m_1t_1+m_2t_2)$ of the total. The coded outputs from the multiplexed coded modulation scheme are provided to modulator **150**, which is representative of conventional television broadcasting circuitry, for transmission of the broadcast HDTV signal on broadcast channel **200**.

The broadcast HDTV signal is received from broadcast channel **200** by receiver **300** which is shown in FIG. 2. The broadcast HDTV signal is received by demodulator **350** which is representative of conventional reception and demodulation circuitry, e.g., the antenna, demodulation, analog-to-digital conversion, etc. Demodulator **350** provides a time-multiplexed digital signal representing the received coded outputs on lead **90** which is processed by demultiplexer **340** to provide the separate received coded outputs. The received coded output representing the more important data is provided to channel decoder **331** and the received coded output representing the less important data is provided to channel decoder **332**. Channel decoder **331** (**332**) decodes the received coded output representing the more important (less important) data to provide the more important (less important) data, i.e., class of information, to source decoder **310**. Source decoder **310** provides the inverse function of source encoder **110** of transmitter **100** to provide the received HDTV signal to CRT display **301**.

Having described the general inventive concept above, various illustrative embodiments of a multiplexed coded modulation scheme will now be described. Although any coded modulation scheme can be implemented in coded modulation circuitry **120** and **130**, the present invention advantageously allows the use of simple channel encoders and constellations of uniformly spaced signal points. For the remainder of the discussion, it is assumed that channel encoders **121** and **131** are implemented using a simple 4D 8-state trellis encoder as shown in FIGS. **3-4** (in FIG. **3**, the boxes labeled "T" are T-second delay elements, the circles labeled "+" are exclusive-or gates, and the bit-converter operates in accordance with FIG. **4**). Further, it will be assumed that signal constellations **122** and **132** are representative of uniformly-spaced QAM constellations and, although differing in size (i.e., numbers of signal points), have the same average power (average energy per signal point).

FIGS. **5-7** illustrate a variety of embodiments of an illustrative multiplexed coded modulation scheme for

different a) values of m_1 and m_2, b) QAM signal constellations, and c) t_1/t_2 multiplexer ratios. FIG. **8** lists various characteristics of these embodiments. The bandwidth efficiency each of these embodiments is four data bits per signaling interval, with the percentage of more important data varying from 37.5% to 62.5% of the total. (It should be noted that these embodiments are for comparison purposes only, e.g., other bandwidth efficiencies can be used, different signal constellations can be used (with different sizes), etc.) For example, applying the above mentioned bandwidth efficiency formula to the embodiment shown in FIG. **5**, i.e., $(m_1=3, m_2=5)$, and $(t_1=t_2=T)$ yields four data bits per signaling interval:

$$\frac{(m_1t_1 + m_2t_2)}{t_1 + t_2} = \frac{3T + 5T}{T + T} = 4$$

In each embodiment, the sizes of the signal constellations and the nominal coding gains for the more important and less important data are determined based on the above assumption that the simple 4D 8-state trellis code of FIGS. **3-4** is used in both channel encoders **121** and **131**.

It should be observed in FIG. **3** that two input bits are coded every two signal intervals to provide three encoded bits (i.e., the delay element of the 4D 8-state trellis code is 2T signaling intervals). The three encoded bits, together with an uncoded input bit, are then converted into two pairs of output bits through the bit converter of FIG. **4**. Each pair of output bits is next used to identify, in the first or second signaling intervals, one out of four 2D subsets of signal points, as shown by the example of constellation (A) in FIG. **5**, where each subset identified by a two bit pattern consists of these signal points. The four 2D subsets are obtained by partitioning the corresponding constellation so that the distance between the signal points in each subset is greater than that between the signal points of the overall constellations, as in the conventional coded modulation. Any number of input bits in excess of three will remain uncoded and be used to select a 2D signal point from each of the two identified 2D subsets (some processing on the uncoded bits may be needed in order to simplify the selection process, e.g., see U.S. Pat. No. 4,941,154, issued Jul. 10, 1990 to L. -F. Wei, and "Multidimensional constellations-Part I: Introduction, figures of merit, and generalized cross constellations," G. D. Forney, Jr. & L. -F. Wei, *IEEE J. Select. Areas Commun.*, vol. SAC-7, pp. 877-892, August 1989).

In each embodiment the real coding gain is expected to be less than its corresponding nominal coding gain, which is due to the large error coefficient associated with the Minimum Squared Euclidean Distance (MSED) of the 4D 8-state trellis code. The Peak-to-Average Power Ratio (PAR) of the three embodiments are determined by the larger constellations used for the less important data, which are all slightly bigger than two.

It may also be noted that additional coded modulation schemes can be implemented within a multiplexed coded modulation scheme to protect against other forms of noise that may be present in a communications system. For example, the conventional coded modulation schemes used in FIGS. **5-7** are not effective against impulse noise, so a well-known Reed-Solomon code

which is effective against impulse noise can be used in conjunction with a trellis code to form a concatenated code. A block diagram of an illustrative embodiment using a concatenated code is shown in FIG. 9. In FIG. 9, the more (less) important data is first separately encoded by first channel encoder **115** (**116**) which uses a well-known Reed-Solomon code (i.e., additional redundant bits are added to m_1 (m_2)), and then further encoded by second channel encoder **121** (**131**) using the trellis code described above (it should be noted that channel encoder **121** (**131**) and constellation mapper **122** (**132**) have to be modified accordingly to handle the additional redundant bits introduced by first channel encoder **115** (**116**)).

The foregoing merely illustrates the principles of the invention. For example, although the invention is illustrated herein as being implemented with discrete functional building blocks, e.g., source decoders, channel encoders, etc., the functions of any one or more of those building blocks can be carried out using one or more appropriate programmed processors, digital signal processing (DSP) chips, etc. In addition, the invention could be implemented such that some of the discrete functional blocks were shared in time, e.g., physically using only one channel encoder that is switched between two signal constellations. Also, the coded modulation scheme for each class of information can be enhanced using interleaving techniques, or more complex coded modulation schemes, to protect against other forms of noise, e.g., to protect against "colored" noise. Further, other multiplexing techniques may be used in place of time-division-multiplexing.

It will thus be appreciated that those skilled in the art will be able to devise numerous and various alternative arrangements which, although not explicitly shown or described herein, embody the principles of the invention and are within its spirit and scope.

We claim:

1. A method for processing an information signal, the information signal being comprised of a plurality of classes of information, the method comprising the steps of:

separately coding each one of the plurality of classes of information using a separate coded modulation scheme to provide a coded output, such that one of the plurality of classes of information has more error protection than the remaining ones of the plurality of classes of information, where each one of the plurality of coded outputs comprises a plurality of signal points taken from a signal point constellation and where the signal point constellation of at least one of the coded modulation schemes is different from the signal point constellations of the remaining coded modulation schemes; and

multiplexing the plurality of coded outputs for transmission.

2. The method of claim **1** wherein the multiplexing step is time-division-multiplexing.

3. The method of claim **2** wherein the multiplexing step includes the step of assigning each one of the plurality of coded outputs to a time interval in a time frame, the time frame being greater than or equal to the sum of the plurality of assigned time intervals.

4. The method of claim **3** wherein at least one of the plurality of time intervals is longer in duration than the remaining ones of the plurality of the time intervals, and said longer time interval is assigned to the one of the plurality of classes of information that has more error protection.

5. The method of claim **1** wherein the information signal is an HDTV signal.

6. The method of claim **1** wherein the separately coding step includes the step of:

encoding each one of the plurality of classes of information to provide an encoded output; and

mapping each one of the plurality of encoded outputs to a signal point of the respective signal point constellation to provide the coded output.

7. The method of claim **6** wherein each one of the plurality of classes of information is comprised of a plurality of data bits.

8. The method of claim **6** wherein the encoding step comprises the step of trellis coding.

9. The method of claim **6** wherein the encoding step comprises the step of encoding with a concatenated code.

10. The method of claim **9** wherein the concatenated code is comprised of a Reed-solomon code and a trellis code.

11. A method for providing unequal error protection for an information signal, the information signal being comprised of a plurality of classes of information, the method comprising the steps of:

assigning each one of the plurality of classes of information to a coded modulation scheme such that at least one of the plurality of classes of information is assigned to a different coded modulation scheme than the remaining ones of the plurality of classes of information;

assigning a time interval to each one of the plurality of coded modulation schemes such that at least one of the plurality of coded modulation schemes is assigned to a different time interval than the remaining ones of the plurality of coded modulation schemes; and

separately coding each one of the plurality of classes of information using the assigned coded modulation scheme in the assigned time interval to provide a coded output for transmission such that at least one of the plurality of classes of information has more error protection than the remaining ones of the plurality of classes of information;

where each one of the coded outputs comprises a plurality of signal points taken from a signal point constellation and where the signal point constellation of at least one of the coded modulation schemes is different from the signal point constellations of the remaining coded modulation schemes.

12. The method of claim **11** wherein at least one of the plurality of assigned time intervals is longer in duration than the remaining ones of the plurality of assigned time intervals, and said longer time interval is assigned to the one of the plurality of classes of information that has more error protection.

13. The method of claim **11** wherein the information signal is an HDTV signal.

14. The method of claim **11** wherein each one of the plurality of classes of information is comprised of m data bits occurring per T second signaling interval, where $m>0$ for each one of the plurality of classes of information, and $T>0$.

15. The method of claim **14** wherein the separately coding step includes the steps of:

encoding the m data bits each for each T second signaling interval occurring in the assigned time

interval to provide m+r data bits per T second signaling interval, where r>0 and is the average number of redundant data bits; and

mapping each one of the m+r data bits occurring each signaling interval in the assigned time interval to a signal point from a signal constellation to provide the signal point each signaling interval in the assigned time interval as the coded output.

16. The method of claim **15** wherein the encoding step comprises the step of trellis coding.

17. The method of claim **15** wherein the encoding step comprises the step of encoding with a concatenated code.

18. The method of claim **15** wherein the concatenate code is comprised of a Reed-Solomon code and a trellis code.

19. Apparatus for processing an information signal, the information signal being comprised of a plurality of classes of information, the apparatus being comprised of:

source encoding means responsive to the information signal for providing the plurality of classes of information;

coding means responsive to the plurality of classes of information for separately coding each one of the plurality of classes of information using a separate coded modulation scheme to provide a coded output for each one of the plurality of classes of information such that at least one of the plurality of classes of information has more error protection then the remaining ones of the plurality of classes of information, where each one of the coded outputs comprises a plurality of signal points taken from a signal point constellation and where the signal point constellation of at least one of the coded modulation schemes is different from the signal point constellations of the remaining coded modulation schemes; and

means for multiplexing the plurality of coded outputs for transmission.

20. The apparatus of claim **19** wherein the means for multiplexing operates in accordance with time-division-multiplexing.

21. The apparatus of claim **19** wherein the means for multiplexing assigns each one of the plurality of coded outputs to a time interval in a time frame, the time frame being greater than or equal to the sum of the plurality of assigned time intervals.

22. The apparatus of claim **19** wherein at least one of the plurality of time intervals is longer in duration than the remaining ones of the plurality of time intervals, and said longer time interval is assigned to the one of the plurality of classes of information that has more error protection.

23. The apparatus of claim **19** wherein the information signal is an HDTV signal.

24. The apparatus of claim **19** wherein the coding means is further comprised of:

means for channel encoding each one the plurality of classes of information to provide an encoded output; and

means for mapping each one of the encoded outputs to signal point of a signal constellation to provide the coded output.

25. The apparatus of claim **24** wherein at least one of the plurality of encoded outputs is mapped to a signal constellation of different size than the remaining ones of the plurality of encoded outputs.

26. The apparatus of claim **24** wherein each one of the plurality of classes of information is comprised of a plurality of data bits.

27. The apparatus of claim **24** wherein the means for channel encoding encodes using a trellis code.

28. The apparatus of claim **24** wherein the means for channel encoding encodes using a concatenated code.

29. The apparatus of claim **28** wherein the concatenated code is comprised of a Reed-Solomon code and a trellis code.

30. Apparatus for decoding a received signal, the received signal representing a stream of signal points, the apparatus being comprised of:

means for demultiplexing the stream of signal points to provide a plurality of coded outputs, where each one of the plurality of coded outputs comprises a portion of the signal points from the stream of signal points and represents a class of information wherein one said coded outputs provides more error protection to its class of information than the remainder of said coded outputs to their classes of information;

a plurality of means for decoding, where each one of the plurality of means for decoding decodes one of the plurality of coded outputs to provide one of the plurality of classes of information; and

means for source decoding the plurality of classes of information to provide an information signal.

31. The apparatus of claim **30** wherein the information signal is an HDTV signal.

32. The apparatus of claim **30** wherein the means for demultiplexing operates in accordance with time-division-demultiplexing.

* * * * *

EXHIBIT G

INFORMATION THEORY AND RELIABLE COMMUNICATION

Robert G. Gallager
Massachusetts Institute of Technology

JOHN WILEY & SONS

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the decoder to count a received block as erased and pass on to the next block. The probability of such erasures, of course, is intimately related to the distribution function of $\overline{W_n}$.

6.10 Coding for Burst Noise Channels

In the previous sections we have been concerned primarily with coding techniques for memoryless channels. In this section we shall be concerned with channels having binary input and output alphabets where the transmission errors tend to cluster together into bursts. Most binary communication systems (with the exception of space channels) exhibit this behavior to some extent. It is difficult to find probabilistic models for these channels that are appropriate for the study of coding. It is not enough to find models that describe the typical behavior of the channel, since it is the atypical behavior that causes decoding errors for any reasonable coding technique. The atypical behavior is caused by a variety of rare events which by their nature resist probabilistic modeling. For this reason we shall not be concerned with the error probability for various coding techniques on these channels, but will find other measures of performance.

The most obvious coding technique to use on channels with burst noise is that of error detection and retransmission. In this technique the source data are encoded by a parity check code (and preferably a cyclic code, for ease of implementation). The syndrome sequence $\mathbf{S}$ is calculated at the receiver and if $\mathbf{S} = 0$, the information digits are accepted as correct. If $\mathbf{S} \neq 0$, the receiver instructs the transmitter to retransmit the given code word. A decoding error occurs here only if transmission errors occur and the error sequence is the same as one of the code words. For an (N,L) parity check code only 2^L of the 2^N sequences of length N are code words, or only 1 of each 2^{N-L} sequences. It can be seen from this that decoding errors can be made negligible with modest values of $N - L$ and that the number of decoding errors is quite insensitive to the detailed statistics of the noise. For a cyclic code both the encoder and decoder in this scheme can be instrumented with $N - L$ stage shift registers (see Figure 6.5.5).

Despite the simplicity of this technique, it has several drawbacks. The first is the need for a reliable feedback link from receiver to transmitter to transmit the retransmission requests. The second is due to a variety of buffering problems introduced at transmitter and receiver by the occasional retransmissions. The third is that if the channel is normally quite noisy, very few code words will be accepted. The seriousness of the first two drawbacks depends upon the existence of a feedback link and the nature of the source (that is, whether it produces data on call from the transmitter or whether it produces data at a constant rate in time). If the third drawback is serious, then the retransmission scheme above can be combined with some of the error

correction techniques to be discussed subsequently. It should be pointed out here that if the digital data modulator and demodulator have been efficiently designed to transmit a large number of binary digits per second, then frequent transmission errors will occur and error correction will certainly be necessary whether or not retransmission is used.

Another simple technique for achieving reliable transmission on a burst noise channel is that of interlacing or scrambling. From a conceptual standpoint, the incoming stream of binary data is separated into a fixed number, say r, of data streams as shown in Figure 6.10.1. Each of the r data streams is

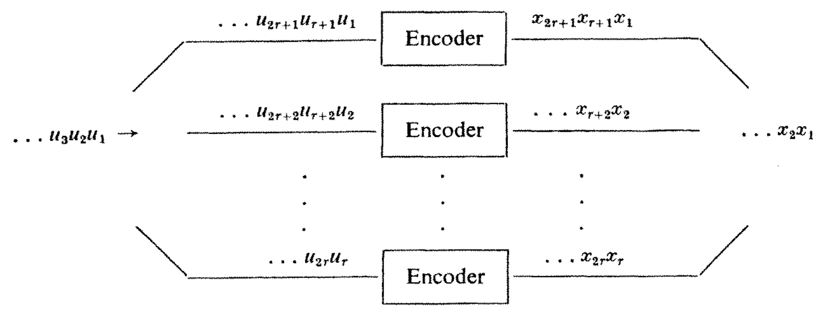

Figure 6.10.1. Interlaced encoding.

then separately encoded and the encoded sequences are commutated together for transmission on the channel. At the channel output, the received data stream is again separated into r streams, each stream is separately decoded, and the decoded data is finally commutated together again.

The idea behind this technique is that successive letters within any code word will be separated on the channel by r channel time units. Thus if the channel memory dies away with increasing time separation, the channel noise affecting successive letters in a code word will be essentially independent for sufficiently large r. Consequently, any of the coding techniques previously discussed for memoryless channels can be used on a burst noise channel in conjunction with interlacing.

It can be seen from the above argument that, in a sense, having memory in a channel does not decrease its capacity. To make this statement more explicit, suppose that a single letter transition probability assignment $P(y \mid x)$ can be defined for a discrete channel with memory.* Then if the channel memory dies out quickly enough in time, any coding technique that yields a given error probability for the discrete memoryless channel with transition

* As discussed in Section 4.6, this is not always possible, and in particular it is not possible for channels with intersymbol interference.

probabilities $P(y \mid x)$ will yield essentially that same error probability for the given channel with memory using interlacing with large enough r. Thus the channel with memory has a capacity at least as large as that of the associated memoryless channel. We shall not state the above result as a theorem because of the difficulty in being precise about how quickly the channel memory must die away with time.

For the implementation of interlacing, it is not always necessary to construct r separate encoders and decoders. For example, if the encoders in Figure 6.10.1 are (N,L) cyclic encoders, each with the generator polynomial $g(D)$, then the interlacing and encoding in Figure 6.10.1 can be replaced by an (Nr,Lr) cyclic encoder with the generator polynomial $g(D^r)$. Likewise if r is odd and the encoders are identical convolutional encoders, each of rate ½ (in bits) as in Figure 6.8.1, then the interlacing and encoding can be replaced with a single convolutional encoder placing $r - 1$ shift register stages between each shift register stage in the diagram of Figure 6.8.1, and by passing the check bits through an $(r - 1)/2$ stage shift register.

The major advantage of interlacing, from a practical standpoint, is that it is quite insensitive to the detailed statistics of the channel memory, relying only on r being large enough to eliminate most of the effects of the memory. The disadvantage of interlacing (or at least of an interlaced decoder) is that the memory is ignored in making decoding decisions.

Before proceeding further we must set up a criterion for evaluating coding techniques for burst noise channels. For simplicity we shall assume throughout that the channel input $\mathbf{x}$ and output $\mathbf{y}$ are binary sequences. The error sequence $\mathbf{z} = \ldots, z_{-1}, z_0, z_1, \ldots$ is given by $\mathbf{x} \oplus \mathbf{y}$. In attempting to define what a burst is, we observe that two errors (i.e., **1**'s) in the sequence $\mathbf{z}$ separated by a number of **0**'s could be interpreted either as two isolated errors or as a burst containing two errors. To resolve this type of ambiguity *we define a set of consecutive noise digits* $z_n, z_{n+1}, \ldots, z_{n+b-1}$ *to be a burst of errors relative to a guard space g if, first,* $z_n = z_{n+b-1} = \mathbf{1}$, *and, second, if the g consecutive digits on each side of the set* $z_n \ldots, z_{n+b-1}$ *are all* **0**, *and third, if there is no consecutive sequence of g* **0**'s *within the set* $z_n, \ldots, z_{n+b-1}$. The length of the burst, b, is taken as the size of the set. Observe that all the noise digits in a burst need not be errors. In the special case $b = 1$, the burst is just an isolated error with at least g error free digits on each side. The above definition uniquely breaks up any $\mathbf{z} = \ldots, z_{-1}, z_0, z_1, \ldots$ into a set of bursts, each separated by at least g error free digits.

An encoder and decoder is said to have burst correcting capability b relative to a guard space g if b is the largest integer for which every noise sequence $\mathbf{z}$ containing only bursts of length b or less relative to the guard space g is correctly decoded. The burst correcting capability of an encoder (or code) relative to a guard space g is similarly defined as the largest integer

b such that for some decoder, the encoder and decoder have burst correcting capability b relative to the guard space g. We shall use the burst capability of a code relative to a given guard space as a criterion of the effectiveness of the code against burst noise. It should be clear that this is only a crude criterion. For example, on a channel where long bursts containing relatively few errors are far more likely than shorter bursts containing many errors, one would prefer a code capable of correcting the likely longer bursts at the expense of the less likely shorter bursts.

We now develop an upper bound on the burst correcting capability of a code in terms of its rate R and its guard space g. The bound is valid for block codes, convolutional codes, and any other class of codes. We do assume,

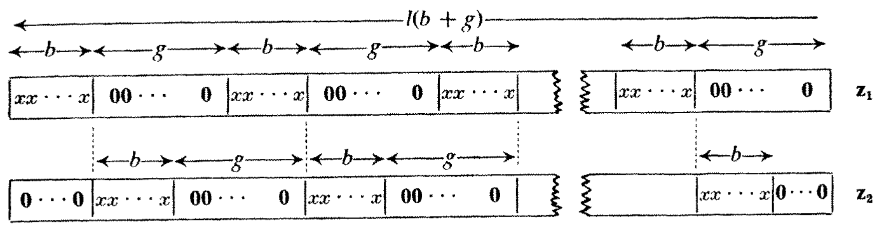

Figure 6.10.2. ***Two types of noise sequences;*** x***'s represent arbitrary binary digits.***

however, that there is an arbitrary but finite decoding delay of, say, N source digits. That is, by the time the nth source digit enters the encoder, $(n > N)$, at least $n - N$ source digits must be decoded. Recalling that the rate R (in binary units) is defined as the number of source digits per channel digit, this condition can be translated into requiring that by the time L channel digits have been received, at least $RL - N$ source digits must be decoded. Now suppose we are using a code that has burst correcting capability b relative to a guard space g, and consider a number of received digits L that is a multiple of $b + g$, $L = l(b + g)$.

Next consider the two types of error sequences shown in Figure 6.10.2. In each type, the error sequence is constrained to have zero values in the positions shown and may have arbitrary values in the positions marked x (we assume here that $b \le g$). Let $\mathbf{x}_1$ and $\mathbf{x}_2$ be encoded sequences corresponding to different choices of the first $[RL - N]$ source digits and $\mathbf{z}_1$ and $\mathbf{z}_2$ be error sequences of the first and second type respectively. Since by assumption these error sequences cannot cause decoding errors, we have

$$\mathbf{x}_1 \oplus \mathbf{z}_1 \neq \mathbf{x}_2 \oplus \mathbf{z}_2 \tag{6.10.1}$$

More generally, if $\mathbf{z}_1$ and $\mathbf{z}_1'$ are error sequences of the first type and $\mathbf{z}_2$ and $\mathbf{z}_2'$ are error sequences of the second type, we must have

$$\mathbf{x}_1 \oplus \mathbf{z}_1 \oplus \mathbf{z}_2 \neq \mathbf{x}_2 \oplus \mathbf{z}_1' \oplus \mathbf{z}_2' \tag{6.10.2}$$

EXHIBIT H

United States Patent [19]

[11] Patent Number: 4,677,625

[45] Date of Patent: Jun. 30, 1987

Betts et al.

[54] DISTRIBUTED TRELLIS ENCODER

[75] Inventors: William L. Betts, St. Petersburg; Kenneth Martinez, Pinellas Park; Gordon Bremer, Clearwater, all of Fla.

[73] Assignee: Paradyne Corporation, Largo, Fla.

[21] Appl. No.: 707,084

[22] Filed: Mar. 1, 1985

[51] Int. Cl.[4] G06F 11/10; H03M 13/22

[52] U.S. Cl. .... 371/43; 340/347 DD; 371/2; 375/26; 375/39

[58] Field of Search .... 340/347 DD; 371/43–45, 371/2; 360/39–42; 375/25, 34, 39

[56] References Cited

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4,087,787	5/1978	Acampora	371/43
4,240,156	12/1980	Doland	371/43
4,500,994	2/1985	McCallister et al.	371/43
4,536,878	8/1985	Rattlingourd et al.	371/43

Primary Examiner—T. J. Sloyan
Attorney, Agent, or Firm—Kane, Dalsimer, Sullivan, Kurucz

[57] ABSTRACT

In the transmitter of a data communication system using QAM, a plurality of trellis coders with delay units are used for forward error correction. The output of each encoder is modulated using QAM to generate sequential baud signal elements. The redundant data bits generated are distributed between several non-consecutive bauds. Likewise, at the receiver a plurality of distributed convolutional decoders are utilized to decode the received signal element. The distributed trellis decoder is self-synchronizing.

11 Claims, 4 Drawing Figures

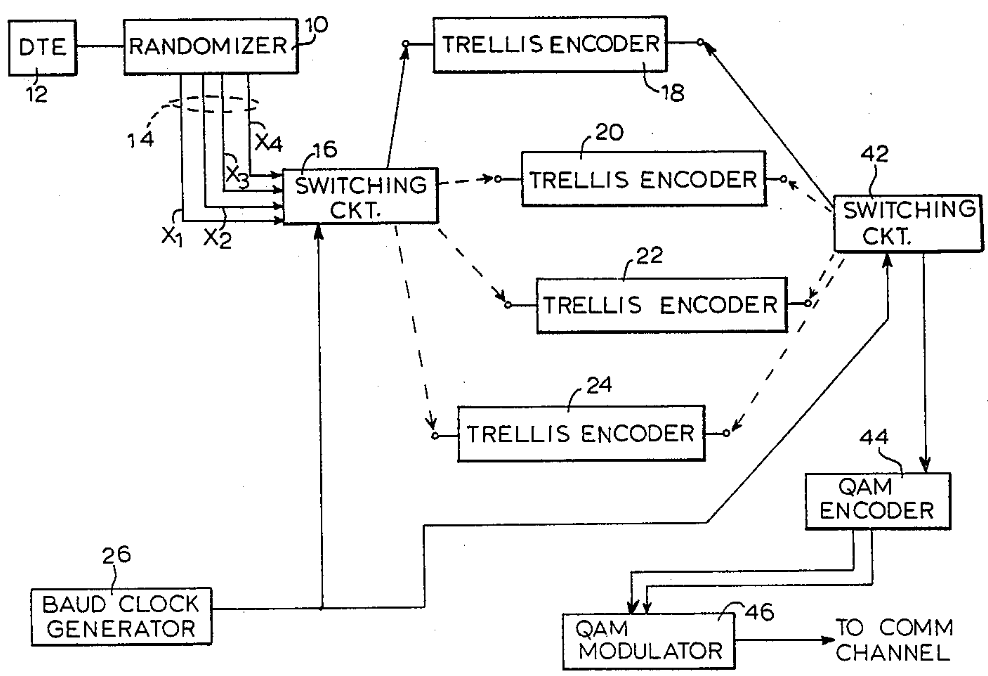
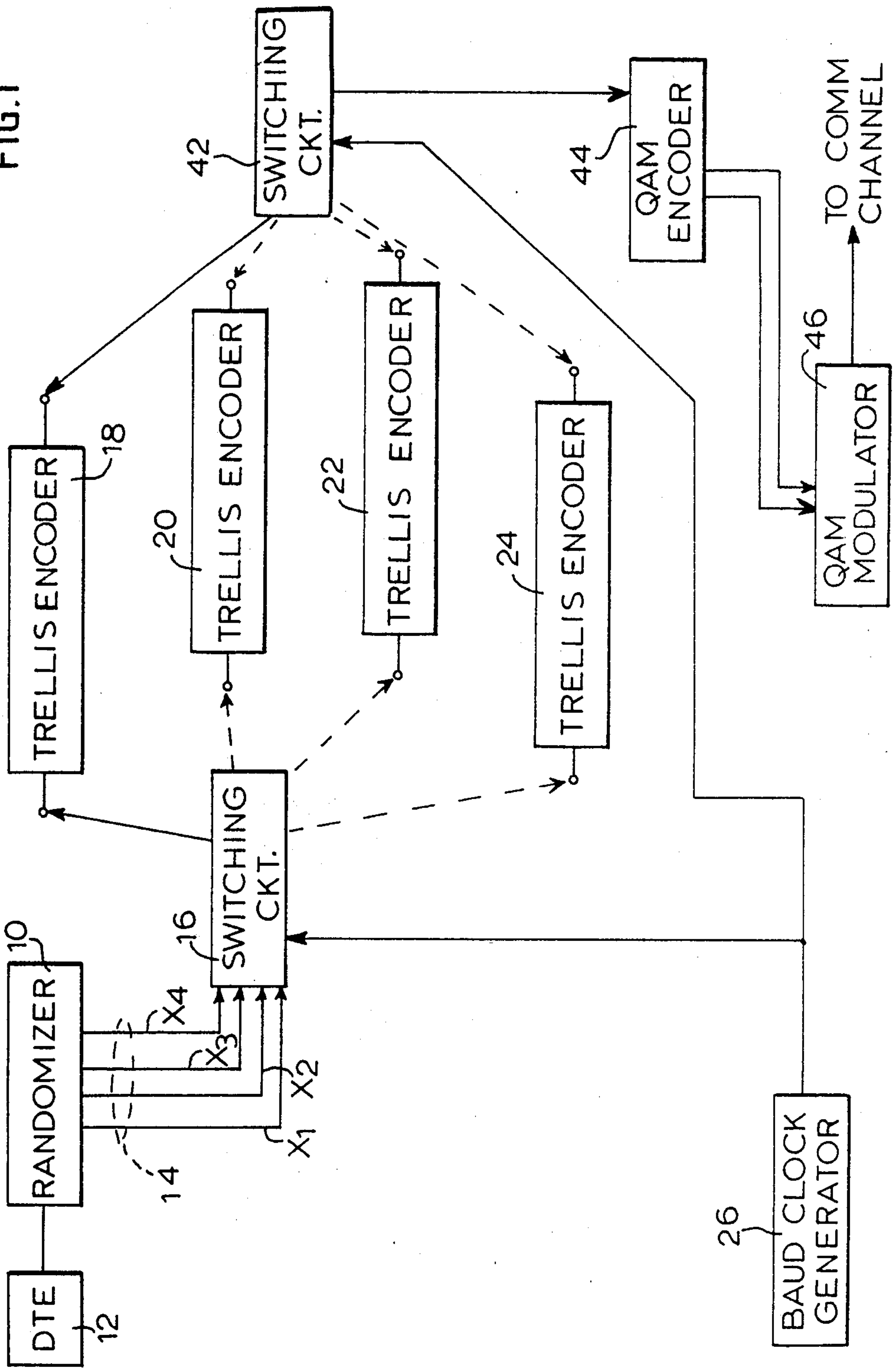


FIG.1


DTE
12
RANDOMIZER
10
14
X1
X2
X3
X4
SWITCHING CKT.
16
TRELLIS ENCODER
18
TRELLIS ENCODER
20
TRELLIS ENCODER
22
TRELLIS ENCODER
24
SWITCHING CKT.
42
QAM ENCODER
44
QAM MODULATOR
46
TO COMM CHANNEL
BAUD CLOCK GENERATOR
26

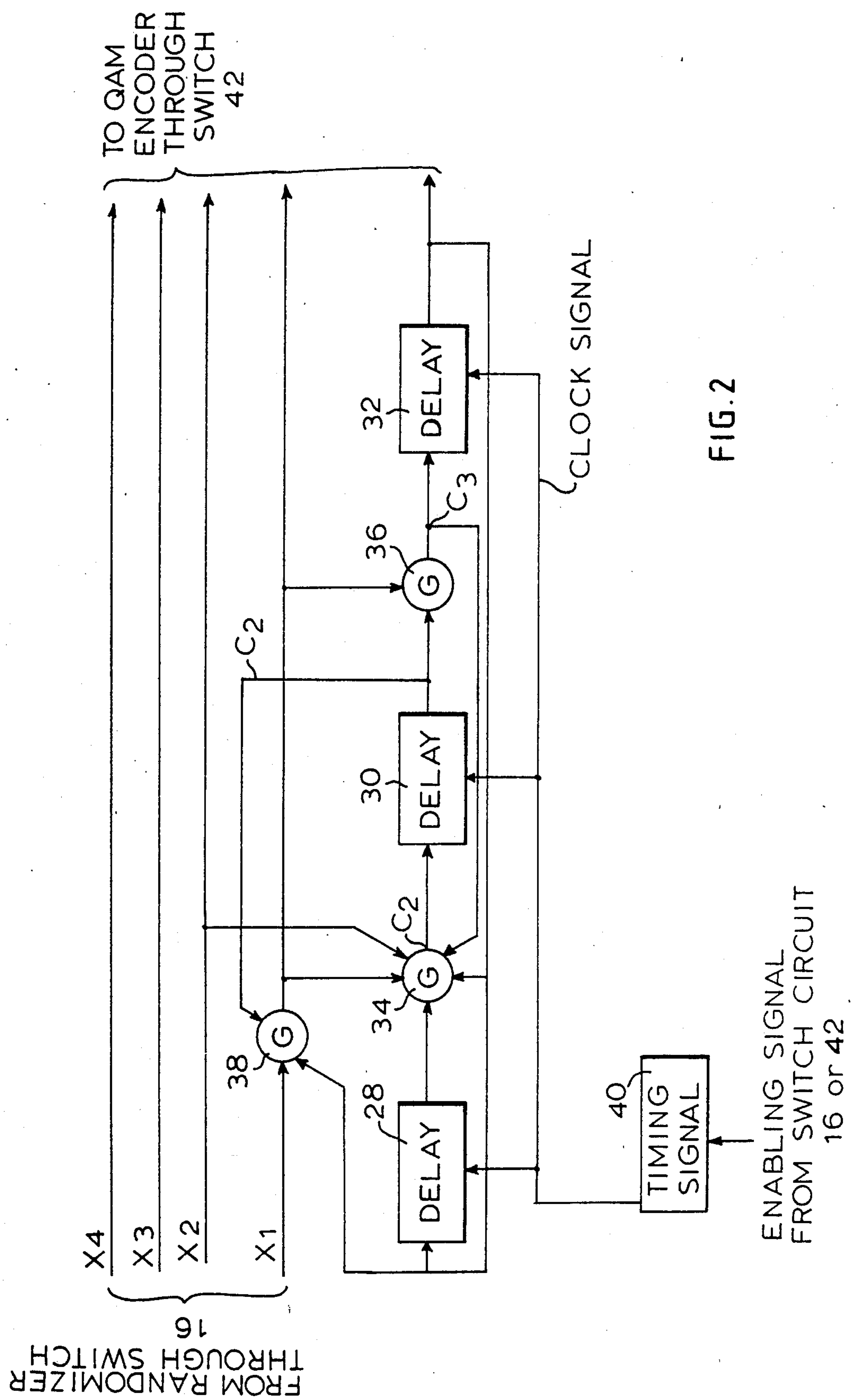
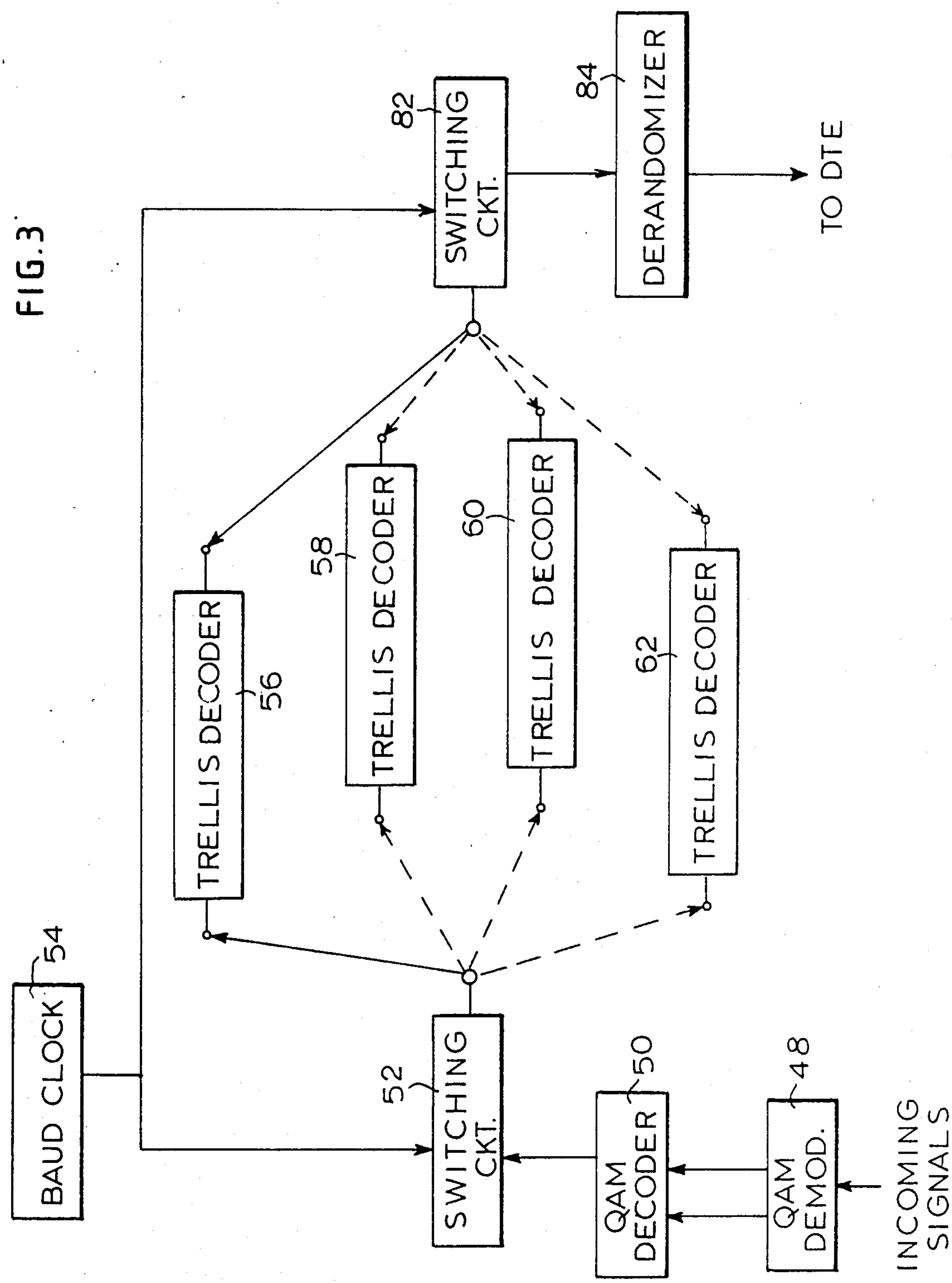

TO QAM ENCODER THROUGH SWITCH 42
X4
X3
X2
X1
FROM RANDOMIZER THROUGH SWITCH 16
28
DELAY
30
DELAY
32
DELAY
34
G
36
G
38
G
C2
C2
C3
CLOCK SIGNAL
40
TIMING SIGNAL
ENABLING SIGNAL FROM SWITCH CIRCUIT 16 or 42

FIG. 2



BAUD CLOCK
54
SWITCHING CKT.
52
QAM DECODER
50
QAM DEMOD.
48
INCOMING SIGNALS
TRELLIS DECODER
56
TRELLIS DECODER
58
TRELLIS DECODER
60
TRELLIS DECODER
62
SWITCHING CKT.
82
DERANDOMIZER
84
TO DTE

FIG. 3

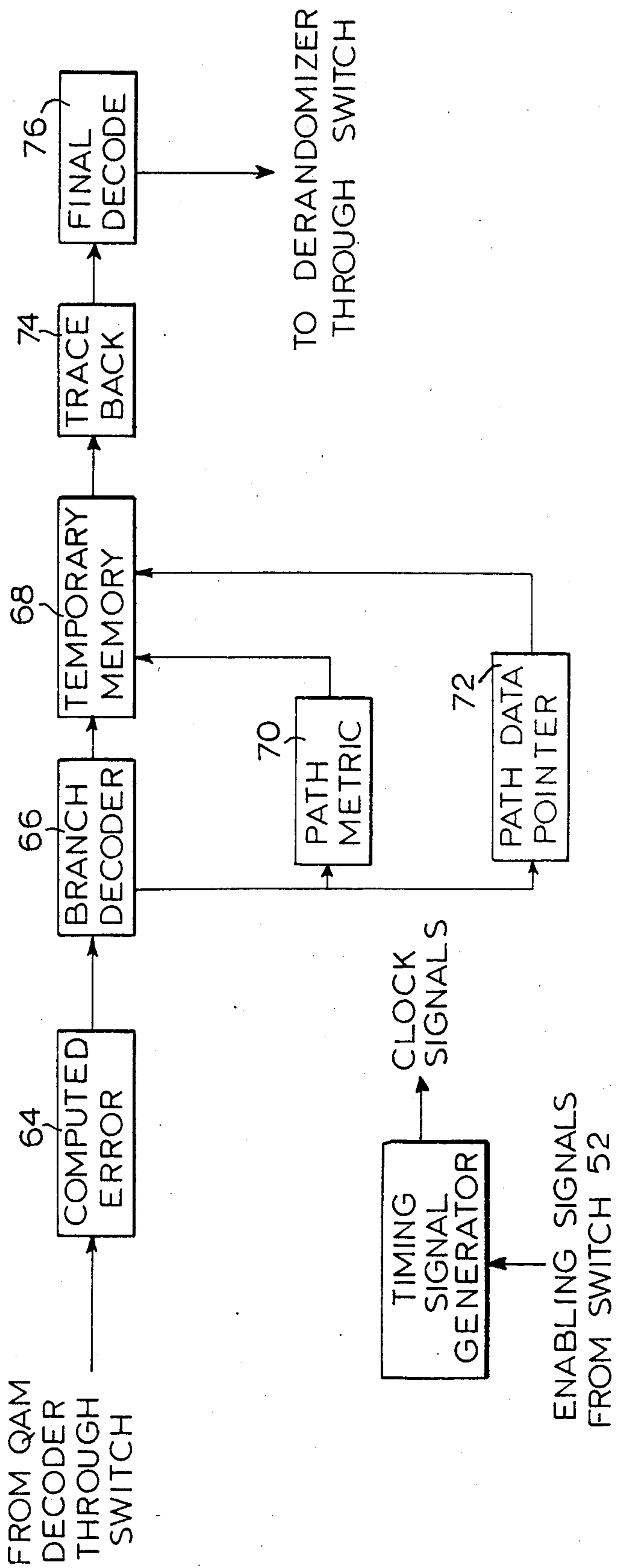

FROM QAM DECODER THROUGH SWITCH
64
COMPUTED ERROR
66
BRANCH DECODER
68
TEMPORARY MEMORY
74
TRACE BACK
76
FINAL DECODE
TO DERANDOMIZER THROUGH SWITCH
70
PATH METRIC
72
PATH DATA POINTER
CLOCK SIGNALS
TIMING SIGNAL GENERATOR
ENABLING SIGNALS FROM SWITCH 52

FIG. 4

DISTRIBUTED TRELLIS ENCODER

RELATED APPLICATIONS

The subject matter of this application is related to U.S. applications Ser. No. 707,085 entitled Self-Synchronizing Interleaver for Trellis Encoder used in Wireline Modems and Ser. No. 707,083 entitled Self-Synchronizing De-Interleaver for Viterbi Decoder Used in Wireline Modems, filed on even date herewith and incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of Invention

This invention pertains to an apparatus and method of encoding binary bits and more particularly to a method and apparatus for making use of a forward error correction scheme for a reduced number of errors at a given signal-to-noise ratio.

2. Description of the Prior Art

Communication networks using high speed data rates require high signal-to-noise ratios for proper data transmission. Numerous schemes and combinations thereof have been proposed to reduce the number of errors at these given signal-to-noise ratios. For example, in U.S. Pat. No. 4,077,021 to Csajka et al a forward error correcting scheme is described making use of the so-called Viterbi algorithm. In a further development described by the CCITT study group XVII, Contribution No. D180, in October, 1983, entitled TRELLIS-CODED MODULATION SCHEME WITH 8-STATE SYSTEMATIC ENCODER AND 90 SYMMETRY FOR USE IN DATA MODEMS TRANSMITTING 3-7 BITS PER MODULATION INTERVAL a two-dimensional trellis for a quadrature amplitude modulation scheme is disclosed having 90° symmetry which results in a 4db gain in the signal-to-noise ratio. Typically, in forward error coding, redundant bits are added systematically to the data bits so that normally only predetermined transitions from one sequential group of bits (corresponding to bauds) to another are allowed. There is an inherent correlation between these redundant bits over consecutive bauds. At the receiver each baud is tentatively decoded and then analyzed based on past history, and the decoded bits are corrected if necessary. However, it was found that certain types of relatively long error signals, such as for exmaple, low frequenty phase jitter, cause a constant phase error in the signal constellation for extended (consecutive baud) periods of time. This type of error prevents or inhibits the correction of the received bits using the schemes described above.

OBJECTIVES AND SUMMARY OF THE INVENTION

A principal objective of the present invention is to provide a device and method for data communication in which the effects of long bursts of error signals such as low frequency phase jitter are minimized.

A further objective is to provide a method of adapting a standard modem to perform the subject method and to provide a method that is self-synchronizing.

Other objectives and advantages of the invention shall become apparent from the following description of the invention.

In the present invention the correlation of the redundant bits of different baud signals is distributed in time prior to encoding at the transmitter. A distributed trellis encoding scheme is used to obtain the redundant bits. At the receiver the received bauds are decoded using a plurality of distributed decoders which extract samples from multiple bauds for trellis decoding. The result is similar to that achieved by interleaving but avoids synchronization problems associated with the conventional complex interleaving processes.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** shows the elements of a data transmitter constructed in accordance with the invention;

FIG. **2** shows the elements of a distributed trellis encoder;

FIG. **3** shows the elements of a receiver for receiving data from the transmitter of FIG. **1**; and

FIG. **4** shows the elements of a distributed trellis decoder.

DETAILED DESCRIPTION OF THE INVENTION

As shown in FIG. **1**, a transmitter according to this invention comprises a randomizer **10** which receives serially a stream of data bits from DTE **12**. The randomizer scrambles the bits in a preselected pattern and generates randomized bits on parallel output lines **14** identified as X1, X2, X3 and X4.

These output lines are fed by an electronic switching circuit **16** to a plurality of identical trellis encoders **18**, **20**, **22** and **24**.

The electronic switching circuit **16** switches the signals from the randomizer **10** to one of the trellis encoders **18**, **20**, **22** and **24**, in accordance with a baud clock signal generated by baud clock generator **26**. In other words, for each baud period all the randomizer outputs X1, X2, X3 and X4 are fed to one of the encoders. Details of the trellis encoders **18**, **20**, **22** and **24** are shown in FIG. **2**.

Each encoder comprises three delay units **28**, **30** and **32** which are adapted to generate a delay of one baud period. The encoder further comprises three gates **34**, **36** and **38**. These gates may be for example XOR (exclusive -OR) gates.

The trellis encoder shown in FIG. **2** is well known in the art and need not be described any further. Preferably all the elements of the encoder are digital elements which are enabled by appropriate clocking signals from timing signal generator **40**. The timing signal generator is enabled only when it receives an appropriate signal from switching circuit **16**. Thus each encoder is active only when it is addressed by switching circuit **16**. At all other times, the trellis encoders are idle.

Outputs Y0, Y1, X2, X3 and X4 are fed from the respective trellis encoders by a second electronic switching circuit **42** to QAM (quadrature amplitude modulation) encoder **44**. Switching circuit **42** is also enabled by baud clock generator **26** so that it operates simultaneously with switching circuit **16**. QAM encoder **44** selects a point of a preselected signal constellation corresponding to the inputs from circuit **42** and generates an in-phase and a quadrature output signal corresponding to said point. These output signals are fed to a QAM modulator **46** which generates corresponding analog QAM signals having a baud period equal to the period of the signals generated by signal generator **26**. The signals from modulator **46** are transmitted over a common data communication channel to a receiver.

In effect the bits of several consecutive signals are spaced out over several bauds by the distributed trellis encoders.

At the receiver, illustrated in FIG. 3, the incoming analog signals are demodulated by a QAM demodulator **48** which generates an in-phase and a quadrature signal which are fed to a QAM decoder **50**. The QAM decoder **50** selects a point on the signal constellation closest to the actual point corresponding to the signals received from QAM demodulator **48**. The bits corresponding to said point are sent to a third electronic switching circuit **52** having a period equal to the baud period of the received signals. Circuit **52** accesses sequentially one of four distributed trellis decoders **56, 58, 60** and **62** in response to the switching signal from generator **54**. Thus all the binary signals from QAM decoder **50** corresponding to each received QAM signal are sent to one of the trellis decoders. The four trellis decoders are standard decoders well known in the art. One such decoder is shown in FIG. 4.

In a typical trellis decoder, the signals from the QAM decoder (in the present case, via switching circuit **52**) are fed into an error computer circuit **64** which generates an error signal based on previously received signals. This error signal is fed to a branch decoder **66**. The branch decoder uses the trellis branch rules (predetermined in accordance with the Viterbi algorithm) to generate a set of possible points corresponding to the received point. These set of points are stored in temporary memory **68**. The decoder then searches through the points of the set to calculate the point with the smallest errors in accordance with appropriate constants stored in the path metric memory **70** and path pointer memory **72**. The smallest error is used by trace back memory **74** to track back the last 4–16 bauds (in accordance with a preselected well-known scheme) to generate the final received point. The final received point of the set of points in memory **68** is fed to final decoder **76** as the received point.

As with the encoder of FIG. 2, each decoder comprises digital elements which are enabled by a timing signal generator **78**.

The timing signal generator is enabled by an appropriate signal from switching circuit **52** only when the respective decoder is addressed by the switching circuit. Generator **78** generates clocking signals for the various decoder elements. Thus each decoder **56, 68, 60** and **62** is active only when it is addressed by switching circuit **52**, and otherwise it is idle.

The output of each decoder is accessed sequentially by a fourth electronic switching circuit **82** which is synchronized by the baud clock generator **54** so that it is in step with switching circuit **52**. In other words, each trellis decoder is accessed simultaneously by switch circuits **52** and **82**. The switching circuit **82** feeds the signals from the decoders to derandomizer **84** for reversing the effects of randomizer **10** and then to a user DTE.

It can be seen from the above description that switching circuits **16** and **52** acts as multiplexers while switch circuits **42** and **82** act as demultiplexers. The effect of this switching is to interleave the data bits at the transmitter across four bauds, and deinterleave these bits at the receiver. Obviously the trellis encoders are self-synchronized so that no synchronizing signals are needed between the transmitter and receiver

In the above description consecutive bits are interleaved across four bauds by using four distributed trellis encoders and decoders. Obviously if more encoders and decoders are used the number of bauds over which interleaving occurs increases.

It should be appreciated that the invention makes use of standard QAM encoders, modulators, decoders, demodulators and standard trellis encoders and decoders which are well known in the art. Furthermore, while baud clock generators **26** and **54** are described as separate elements, in practice they can be incorporated in the QAM modulator and demodulator respectively. All the circuits of FIGS. **1** and **3** may be implemented by using a digital microprocessor.

Obviously, numerous modifications to the subject application may be made without departing from the scope of the invention as defined in the appended claims.

What is claimed is:

1. A data transmission section for a modem coupled to a channel for sending data signals comprising:

1. A plurality of trellis encoders, each trellis encoder having an input for receiving n plain text bits, each encoder being provided to interleave bits received by the encoder during a first baud period with bits received during more than two previous baud periods to generate n trellis encoded bits, k, being larger than one; in a single baud period, each trellis encoder having means for delaying at least some of said n plain text bits so that they may be outputted and combined with bits outputted from one or more other trellis encoders during single baud periods;
2. encoder activating means for selectively activating only one of said trellis encoders for one baud period in a preselected sequence whereby bits received during a baud period i are interleaved with bits received during a baud period i-k;
3. signal encoding means for converting encoded bits into signals suitable for transmission over said channel; and
4. transmitter switching means for feeding n plain text bits per baud period to the activated trellis encoder and for sending the encoded bits from the activated trellis encoder to the signal encoding means.

2. A receiver section for a modem receiving data signals from a channel, said signals having been trellis encoded by interleaving bits corresponding to a baud period i with bits corresponding to a baud period i-k, k being larger than two, and having:

1. a demodulator and a decoder connected to the output of said demodulator for converting analog data signals from said channel into multiple series of bits, each series of bits substantially corresponding to a point of said analog data signal's preselected signal constellation;
2. k trellis decoders, each trellis decoder having an input from said decoder for receiving series of bits from said decoder and generating n bits of plain text bits corresponding to n bits received at least during two previous baud periods;
3. decoder activating means for activating only one of said trellis decoders during one baud period in another predetermined sequence; and
4. receiver switching means for feeding n encoded bits to the activated decoder and for collecting n plain text bits from the activated decoder.

3. A method of transmitting a plurality of input data bits over a channel by quadrature amplitude modulator comprising:

providing a plurality of trellis encoders, each encoder using an identical scheme to interleave bits received during a first baud period with bits received during more than two earlier baud periods preceding said first baud period to generate output bits;

activating each of said trellis encoders in a preselected order for a baud period;

feeding bits which occur during a single baud period to only one of said plurality of trellis encoders;

delaying at least some of said bits in said one trellis encoder during a single baud period;

combining bits which have been outputted from said one trellis encoder with bits which have been outputted from one or more different trellis encoders for transmission during a single baud period; and

quadrature amplitude modulating output bits of each activated trellis encoder.

4. A system for transmitting data signals over a data channel comprising:

a. a data transmission section coupled to said channel for sending data signals and having:

1. A plurality of trellis encoders, each trellis encoder having an input for receiving n plain text bits each encoder being provided to combine bits received by the encoder during more than two previous baud periods with bits received during a previous baud period to generate n trellis encoded bits in a single baud period, each trellis encoder having means for delaying at least some of said n plain text bits so that they can be outputted and combined with bits outputted from one or more other trellis encoders during single baud periods;
2. encoder activating means for selectively activating only one of said trellis encoders for one baud period in a preselected sequence;
3. signal encoding means for converting encoded bits into signals suitable for transmission over said channel; and
4. transmitter switching means for feeding n plain text bits per baud period to the activated trellis encoder and for sending the encoded bits from the activated trellis encoder to the signal encoding means; and

b. a receiver section for receiving data signals from said channel, and having:

1. a demodulator and a decoder connected to the output of said demodulator for converting analog data signals from said channel into multiple series of bits, each series of bits substantially corresponding to a point of said analog data signal's preselected signal constellation of;
2. a plurality of trellis decoders equal in number to the trellis encoders, each decoder generating n bits of plain text bits corresponding to n bits received by the encoder during a baud period and n bits received at least during a previous baud period;
3. decoder activating means for activating only one of said trellis decoders during one baud period in another predetermined sequence; and
4. receiver switching means for feeding n bits to the activated decoder and for collecting n plain text bits from the activated decoder.

5. The system of claim **4** wherein said transmitter switching means comprises a first transmitter switch for providing input bits to the activated trellis encoder, and a second transmitter switch for providing encoded bits from the activated trellis encoder to the signal encoding means.

6. The system of claim **5** wherein said signal encoding means comprises a quadrature amplitude modulator.

7. The system of claim **6** wherein said signal decoding means comprises a quadrature amplitude demodulator.

8. The system of claim **7** wherein there are k trellis encoders each trellis encoders including several delay elements for combining the bits received during said one baud periods with bits received during several preceding baud periods each preceding baud period being separated from the next baud period by $(k-1)$ D seconds where D is the duration of a period.

9. The system of claim **7** wherein said receiver switching means comprises a first receiver switch for feeding encoded bits to the activated decoders and a second receiver switch for collecting plain text bits from the activated decoders.

10. The system of claim **7** wherein each period has a time duration of D seconds and each encoder includes a delay element for delaying bits received during a baud period by D seconds.

11. The method of claim **3** further comprising providing a plurality of trellis decoders for sequentially decoding transmitted signals, each trellis decoder being activated sequentially for a baud period for deinterleaving said signals.

* * * * *

TAB 8

Exhibit A

Claim Charts For U.S. Patent No. 5,243,627

Claim	Claim Element	Evidence of Infringement
1.	Apparatus for forming a stream of trellis encoded signal points in response to input information,	Rembrandt does not express a position at this time as to whether this portion of the preamble of this claim limits the claim's scope. Nevertheless, Rembrandt identifies below aspects of the Accused Instrumentalities that correspond to this portion of the claim preamble. The Accused Instrumentalities are television transmitters that transmit digital television signals in compliance with the ATSC Standard. The ATSC Standard provides that terrestrial broadcast signals be trellis encoded to generate a stream of trellis encoded VSB signal points. (*See, e.g.*, ATSC Digital TV Standard (original), pp. 51-55; Revision B, pp. 56-59; Revision C, pp. 63-67; Revision D, pp. 67-71.)
	said apparatus comprising means for generating a plurality of streams of trellis encoded channel symbols in response to respective portions of said input information,	The Accused Instrumentalities include electronics and/or one or more processors executing code that implement the following features. ATSC Standard compliant transmitters necessarily have twelve trellis encoders operating in parallel, or an equivalent circuit or software module. (*See, e.g.*, ATSC Standard Revision B, Figure D8, p. 57 and associated text.) Each trellis encoder receives a stream of 8-bit Reed-Solomon symbols generated by an upstream Reed-Solomon encoder. (*See, e.g.*, ATSC Digital TV Standard (original) Figure 1, p. 47, Figure 5, p. 51, Table 2, p. 54 and p. 50; Revision B, Figure D1, p. 51, Figure D5, p. 55, Table D2, p. 59, and pp. 54-55; Revision C, Figure Dl, p. 58, Figure D5, p. 62, Table D2, p. 66 and pp. 61-62; Revision D, Figure D5.1, p. 60, Figure D5.2, p. 61, Figure D5.6, p. 66, Table D5.2, p. 70, and pp. 65-66.) Each trellis encoder trellis encodes each received Reed-Solomon symbol in response to the symbols to generate a trellis encoded channel symbol. As each trellis encoder generates successive trellis encoded channel symbols, it generates a stream of trellis encoded channel symbols. The twelve trellis encoders therefore generate a plurality of streams of trellis encoded channel symbols. In the event this limitation is construed or applied in such a way that it is found not to be literally present in the Accused Instrumentalities, Rembrandt contends that the Accused Instrumentalities meet the recited limitation under the doctrine of equivalents, because any purported differences between the

		recited limitation and the aforementioned features of the Accused Instrumentalities are insubstantial.[1] The aforementioned features perform substantially the same function (generating respective streams of encoded data in response to respective portions of an input stream), in substantially the same way (using multiple convolutional encoders or emulators), to achieve substantially the same result (streams of encoded data). This claim element may include features that relate to software of the Accused Instrumentalities, and Rembrandt reserves the right to supplement or modify these contentions.
	each of said channel symbols being comprised of a plurality of signal points, and	The Accused Instrumentalities include electronics and/or one or more processors executing code that implement the following features. Each trellis encoded channel symbol encoded by one of the twelve trellis encoders in an ATSC compliant transmitter comprises four Vestigial Sideband (VSB) values (signal points), that are provided to the VSB modulator. (*See, e.g.*, ATSC Digital TV Standard (original), pp. 51-52; Revision B, pp. 56-57; Revision C, pp. 63-64; Revision D, pp. 67-69.) In the event this limitation is construed or applied in such a way that it is found not to be literally present in the Accused Instrumentalities, Rembrandt contends that the Accused Instrumentalities meet the recited limitation under the doctrine of equivalents, because any purported differences between the recited limitation and the aforementioned features of the Accused Instrumentalities are insubstantial. The aforementioned features perform substantially the same function (providing an encoded signal from a transmitter that uses multiple convolutional encoders or an emulation thereof), in substantially the same way (generating, for respective input values processed by a convolutional encoder, multiple output values for controlling a digital modulator), to achieve substantially the same result (producing multiple values for controlling the output of a digital modulator), as the recited limitation. This claim element may include features that relate to software

[1] Any use within these charts of the words "limitation" or "portion" of a claim are for convenience, and do not constitute any admission that such language within the claim forms the boundaries of a claim element for purposes of the doctrine of equivalents. Moreover, no statement in these contentions should be construed as an admission that any language of the preamble is limiting. Rembrandt takes no position at this time regarding whether any language of any preamble is limiting.

		of the Accused Instrumentalities, and Rembrandt reserves the right to supplement or modify these contentions.
	means for interleaving the signal points of said generated channel symbols to form said stream of trellis encoded signal points,	The Accused Instrumentalities include electronics and/or one or more processors executing code that implement the following features. ATSC Standard compliant transmitters necessarily have an output multiplexer, or an equivalent interleaving circuit or software module, that interleaves the signal points output by respective ones of the twelve trellis encoders and outputs, for a given segment, one signal point from each trellis encoder every twelve time periods, thus forming a stream of trellis encoded signal points. (*See, e.g.*, ATSC Digital TV Standard (original), Table 2, p. 54; Revision B, Table D2, p. 59; Revision C, Table D2, p. 66; Revision D, Table D5.2, p. 70.) In the event this limitation is construed or applied in such a way that it is found not to be literally present in the Accused Instrumentalities, Rembrandt contends that the Accused Instrumentalities meet the recited limitation under the doctrine of equivalents, because any purported differences between the recited limitation and the aforementioned features of the Accused Instrumentalities are insubstantial. The aforementioned features perform substantially the same function (intermixing values for a digital modulator), in substantially the same way (arranging the output values from a single encoder in a pre-determined manner), to achieve substantially the same result (a stream of intermixed values in which values from multiple encoders are intermixed together according to the prearranged pattern), as the recited limitation. This claim element may include features that relate to software of the Accused Instrumentalities, and Rembrandt reserves the right to supplement or modify these contentions.
	said interleaving being carried out in such a way that the signal points of each channel symbol are non-adjacent in said stream of trellis encoded signal points	The Accused Instrumentalities include electronics and/or one or more processors executing code that implement the following features. The signal points (VSB values) from each trellis encoded channel symbol (trellis encoded Reed-Solomon symbol) in an ATSC compliant transmitter are non-adjacent in the stream of trellis encoded signal points. (*See, e.g.*, ATSC Digital TV Standard (original), Table 2, p. 54; Revision B, Table D2, p. 59; Revision C, Table D2, p. 66; Revision D, Table D5.2, p. 70.) In the event this limitation is construed or applied in such a way that it is found not to be literally present in the Accused

		Instrumentalities, Rembrandt contends that the Accused Instrumentalities meet the recited limitation under the doctrine of equivalents, because any purported differences between the recited limitation and the aforementioned features of the Accused Instrumentalities are insubstantial. The aforementioned features perform substantially the same function (separating the output values of a given convolutional encoder that correspond to a single input symbol), in substantially the same way (intermixing output values from respective convolutional encoders), to achieve substantially the same result (creating a stream of output values for controlling the input of a digital modulator, so the values corresponding to a single input symbol are spaced apart in the stream), as the recited limitation. This claim element may include features that relate to software of the Accused Instrumentalities, and Rembrandt reserves the right to supplement or modify these contentions.
	and such that the signal points of adjacent symbols in any one of said channel symbol streams are non-adjacent in said stream of trellis encoded signal points.	The Accused Instrumentalities include electronics and/or one or more processors executing code that implement the following features. The signal points that make up adjacent trellis encoded channel symbols generated by any given trellis encoder in an ATSC compliant transmitter are themselves non-adjacent in the output stream. (*See, e.g.*, ATSC Digital TV Standard (original), Table 2, p. 54; Revision B, Table D2, p. 59; Revision C, Table D2, p. 66; Revision D, Table D5.2, p. 70.) In the event this limitation is construed or applied in such a way that it is found not to be literally present in the Accused Instrumentalities, Rembrandt contends that the Accused Instrumentalities meet the recited limitation under the doctrine of equivalents, because any purported differences between the recited limitation and the aforementioned features of the Accused Instrumentalities are insubstantial. The aforementioned features perform substantially the same function (separating the output values of a given convolutional encoder that correspond to adjacent input symbols to that encoder), in substantially the same way (intermixing output values from multiple respective convolutional encoders), to achieve substantially the same result (creating a stream of output values for controlling the input of a digital modulator, so the values corresponding to adjacent input symbols for a given convolutional encoder are spaced apart in the stream), as the recited limitation.

		This claim element may include features that relate to software of the Accused Instrumentalities, and Rembrandt reserves the right to supplement or modify these contentions.
2.	The apparatus of claim 1 wherein said means for generating generates three of said streams of trellis encoded channel symbols,	The Accused Instrumentalities include electronics and/or one or more processors executing code that implement the following features. ATSC Standard compliant transmitters necessarily have twelve trellis encoders operating in parallel, or an equivalent circuit or software module. (*See, e.g.*, ATSC Standard Revision B, Figure D8, p. 57 and associated text.) Each trellis encoder receives a stream of 8-bit Reed-Solomon symbols generated by an upstream Reed-Solomon encoder. (*See, e.g.*, ATSC Digital TV Standard (original) Figure 1, p. 47, Figure 5, p. 51, Table 2, p. 54 and p. 50; Revision B, Figure D1, p. 51, Figure D5, p. 55, Table D2, p. 59, and pp. 54-55; Revision C, Figure Dl, p. 58, Figure D5, p. 62, Table D2, p. 66 and pp. 61-62; Revision D, Figure D5.1, p. 60, Figure D5.2, p. 61, Figure D5.6, p. 66, Table D5.2, p. 70, and pp. 65-66.) Each trellis encoder trellis encodes each received Reed-Solomon symbol in response to the symbols to generate a trellis encoded channel symbol. As each trellis encoder generates successive trellis encoded channel symbols, it generates a stream of trellis encoded channel symbols. The twelve trellis encoders therefore generate at least three streams of trellis encoded channel symbols. In the event this limitation is construed or applied in such a way that it is found not to be literally present in the Accused Instrumentalities, Rembrandt contends that the Accused Instrumentalities meet the recited limitation under the doctrine of equivalents, because any purported differences between the recited limitation and the aforementioned features of the Accused Instrumentalities are insubstantial. The aforementioned features perform substantially the same function (generating respective streams of encoded data in response to respective portions of an input stream), in substantially the same way (using multiple convolutional encoders or emulators), to achieve substantially the same result (at least three streams of encoded data). This claim element may include features that relate to software of the Accused Instrumentalities, and Rembrandt reserves the right to supplement or modify these contentions.

TAB 9

IN THE UNITED STATES DISTRICT COURT

FOR THE DISTRICT OF DELAWARE

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In re:

REMBRANDT TECHNOLOGIES, LP MDL Docket No.07-md-1848(GMS)

PATENT LITIGATION CHIEF JUDGE GREGORY M. SLEET

-------------------------x

June 23, 2008

10:06 a.m.

VIDEOTAPED DEPOSITION of RICHARD D. GITLIN, taken by Attorneys for Rembrandt Technologies, pursuant to Claim Construction, at the offices of Weil Gotshal & Manges, 757 Fifth Avenue, New York, New York, before Amy Klein, a Shorthand Reporter and Notary Public within and for the State of New York.

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APPEARANCES:

MORGAN & FINNEGAN, L.L.P.
Attorneys for Rembrandt Technologies
3 World Financial Center
New York, New York 10281-2101
BY: SERGEY KOLMYKOV, ESQ.
-and-
ZACHARY D. SILBERSHER, ESQ.

DAY PITNEY LLP
Attorneys for Sharp Corporation
and Sharp Electronics Corp.
One Canterbury Green
201 Broad Street
Stamford, Connecticut 06901-2047
BY: JONATHAN B. TROPP, ESQ.

MARSHALL, GERSTEIN & BORUN LLP
Attorneys for Charter Communications
233 South Wacker Drive
6300 Sears Tower
Chicago, Illinois 60606-6357
BY: CHARLES E. JUISTER, ESQ.

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APPEARANCES (CONTINUED):

ORRICK, HERRINGTON & SUTCLIFFE LLP
Attorneys for FOX Broadcasting
1000 Marsh Road
Menlo Park, California 94025-1015
BY: FABIO E. MARINO, ESQ.

WEIL GOTSHAL & MANGES LLP
Attorneys for ABC, NBC and CBS
767 Fifth Avenue
New York, New York 10153
BY: TIMOTHY E. DeMASI, ESQ.

ALSO PRESENT:
ANDRE SPKTOR - Summer Associate
Weil Gotshal & Manges LLP

JOSE RIVERA, LVS

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THE VIDEO OPERATOR: This is Tape Number 1 in the videotaped deposition of Mr. Richard Gitlin in the matter of In Re Rembrandt Technologies, LP, Patent Litigation, in the United States District Court for the District of Delaware, Case Number 07 MD 1848 (GMS).

This deposition is being held at Weil Gotshal, 767 Fifth Avenue, New York, New York, on June 23, 2008, at approximately 10:06 a.m.

My name is Jose Rivera from the firm of Elisa Dreier Reporting Corp., and I'm the legal video specialist.

The court reporter is Amy Klein in association with Elisa Dreier Reporting Corp., located at 780 Third Avenue.

For the record, will counsel please introduce themselves.

MR. KOLMYKOV: Serge Kolmykov, Morgan & Finnegan, representing Rembrandt.

MR. SILBERSHER: Richard Silbersher from Morgan & Finnegan representing Rembrandt.

MR. TROPP: Jonathan Tropp of Day Pitney representing Sharp Corporation and Sharp Electronics Corporation.

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MR. JUISTER: Charles Juister representing Charter Communications.

MR. MARINO: Fabio Marino from Orrick, Herrington & Sutcliffe for Fox.

MR. DeMASI: Tim DeMasi for Weil Gotshal for ABC, NBC, CBS.

And I'm here with a summer associate, Andre Spktor.

THE VIDEO OPERATOR: Now will the court reporter please swear in the witness.

RICHARD D. GITLIN,
having been first duly sworn by the Notary Public (Amy Klein), was examined and testified as follows:

EXAMINATION BY
MR. KOLMYKOV:

Q. Good morning, Dr. Gitlin.
A. Good morning.
Q. My name is Serge Kolmykov and I represent Rembrandt.
Have you ever had your deposition taken before?
A. Yes.
Q. Where would that be? In which cases?

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A. I appeared as a fact witness in my years at Bell Laboratories several times, and I've done a deposition in an ongoing case now in ITC in Washington.

Q. Can you please identify the parties in that ITC litigation?

A. The Interdigital versus Nokia and Samsung, but now it's just Interdigital versus Samsung.

Q. Thank you.

You might be aware, but I will reiterate, there are some guidelines that you should be aware of.

I will be asking questions. The reporter will take down the question and the answer.

You should answer the question as presented. If for some reason you don't understand my question, ask me to clarify it and I will try to rephrase the question or clarify it for you. But if you answer the question, I will assume that you understand my question.

You may not confer with Defendants' attorneys regarding any part of the deposition

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until I have completed my examination. That means you cannot confer with counsel during the questioning or during breaks.

The only exception is that you don't answer if there is attorney-client privileged information.

MR. TROPP: If I may, I'm sorry to stop you this early, we do reserve our right to confer with the witness with respect to appropriate issues as they may arise. I'm not suggesting that they will arise. But I just don't want my silence to be construed as accepting the way you framed that particular instruction.

MR. KOLMYKOV: Understood. As long as there's no coaching the witness.

MR. TROPP: It is not my intention to coach the witness.

BY MR. KOLMYKOV:

Q. Under the rules Defendants' counsel must make objections to my question on the record. I'm not required to respond to these objections. You should also ignore this objection, because it does not involve your answer to the question.

You should answer the question fully and

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truthfully, to the best of your ability, unless there's an instruction given to you not to answer by your attorney.

Is there anything that would prevent you from providing complete, accurate and truthful testimony today?

A. No.

Q. Do you understand your testimony today is under oath mas if given in court?

A. Yes, I do.

Q. Thank you.

Do you understand what the purpose of this deposition is?

A. In general, I do.

Q. What are -- what do you think the purpose is, the general purpose of this deposition is?

A. You're going to ask me some questions about my declaration.

Q. Okay.

And you understand that you are testifying today as an expert for all other parties?

And by that I refer to all Defendants or

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Counterclaim Plaintiffs in the Rembrandt Technologies LP multi-district litigation.

MR. TROPP: Objection.

Do you want me to specify the basis for my objection?

MR. KOLMYKOV: Yes, please.

MR. TROPP: The NBL case includes effectively two separate, discrete, parallel-track lawsuits: One involving eight patents that are not at issue today, and one involves the '627 patent that is at issue today. And not all Defendants involved in the eight-patent in fact are people who retained Dr. Gitlin.

So he is here today in his capacity as a person who is retained by the Defendants who have an interest in the '627 patent.

MR. KOLMYKOV: Okay, I understand. I agree with your statement.

BY MR. KOLMYKOV:

Q. What do you consider to be your area of expertise?

A. Digital communications and networking.

Q. I'm going to mark your declaration as Exhibit 1.

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(Gitlin Exhibit 1 marked for identification, declaration of Richard Gitlin.)
BY MR. KOLMYKOV:
Q. Have you seen this document before?
A. The document you just gave me?
Q. Yes.
A. Yes.
Q. Did you prepare it?
A. Yes.
Q. The entirety of this document, you prepared the entirety of this document?
A. There are attachments which are reprints. So you gave me Exhibit 1, which includes my CV, which I prepared. It has a whole bunch of references written by other people. Of course I was not involved in that.
And the declaration, yes, I prepared that.
Q. You understand that your declaration is addressing some of the claim construction issues relating to the '627 patent?
A. Yes, I do.
Q. Have you reviewed the parties' claim construction in this case in connection with the

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'627 case?
A. Yes. Yes, I have.
Q. At which point in time did you review those constructions?
A. When I was preparing the declaration I looked at some claim constructions that were done earlier. And recently I looked at I think the most recent claim construction.
Q. And when you state "some claim constructions that were done earlier," which claim constructions are you talking about?
A. They were claim constructions given to me by the attorneys. I don't recall the dates of them.
Q. But you're stating that there were two versions of the claim constructions that were provided to you?
A. I -- yes. I believe I saw -- I think they were basically the same. They were in different printed formats. One had Rembrandt -- the claim constructions separately from the Defendants' claim construction.
Then I saw a document which had them side by side.

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As far as I can recall, the -- the words were the same.
Q. At which point did you form your opinion as to the meaning of the claim terms as they were identified in the claim constructions?
A. When I was working on the declaration (indicating).
Q. Did you form your opinion prior to receiving the claim constructions from counsel?
A. No. I received claim constructions which I had, which I read and understood, and that was what I used in part in preparing my declaration.
Q. So you used those claims constructions provided to you by counsel in preparing your declaration?
A. Yes, I did.
Q. Did you agree with all the claim constructions provided to you by counsel?
A. In --
MR. TROPP: Objection.
A. In my report I only commented on a subset of the claim terms. And those were the ones that I focused on.

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Q. You're stating that you've commented on only a portion of the claim terms. Which claim terms are you referring to exactly?
A. The signal point and trellis encoded channel symbol.
Q. Did you get to review the other claim terms, other than signal point and the trellis encoded channel symbol?
A. Just -- I would like to look at my declaration for a moment.
Q. Sure.
(The witness reviews document.)
A. I didn't study the other terms, form opinions on the other terms.
Q. You did not?
A. I did not.
Q. Did you think it would be meaningful to study other terms before forming your opinions as to the terms signal point and trellis encoded channel symbol?
A. I was asked to look at those terms and to comment on them, and that's what I did.
Q. So as I understand it, you commented and gave your opinion on the terms signal point and the

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trellis encoded channel symbols without considering the other terms that are part of the claims?

MR. TROPP: Objection.

A. I looked at the claim construction, but I didn't study them. I just read them. And I went on to do what the attorneys asked me to do.

Q. What did you do to prepare for this deposition?

A. Over what time frame are you talking about?

Q. Allow me to rephrase that question.

At which point did you become involved in this patent litigation?

A. A couple of months ago. And I started working on the declaration probably maybe a month before it was due.

Q. And during that month -- during those several months from the point that you started working on this litigation, what did you do to prepare for this case?

MR. TROPP: Objection.

A. I read the patents. I read some material that was provided -- I'll call it legal material -- by the attorneys in terms of

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court-submitted or issued documents, and the claim constructions that existed at that time, as well as reviewed some references that I was aware of and refreshed my memory about.

Q. Did you identify those references on your own?

A. Most of them. I read my book again. I looked at Ungerboek's paper, Lee-Fang Wei's paper. Forney had written a paper.

Q. So you were aware of these references prior to this litigation?

A. Yes.

THE WITNESS: Okay.

Q. Other than the Wei paper -- let me rephrase that question.

Other than the papers attached to your declaration, did you review any other papers?

A. I looked at my book. I looked at the references in the chapter which deals with the subject matter at hand. And I read some of the references that were in my book, but I don't recall specifically.

Q. So your book, together with the references attached to your declaration,

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encompassed the entirety of all the references that you reviewed before forming your opinion as to the claim term constructions?

MR. TROPP: Objection.

A. Well, I also have 40 years' experience in this art.

Q. Okay.

Did your attorneys provide you with any materials in preparation for this deposition?

A. I think they called one or two patents to my attention.

Q. Which -- what were those patents?

MR. TROPP: I'm a little bit concerned about that question. I guess I'm not going to interfere with the deposition at this point, but I assume it's your intention to live by the scheduling order that forecloses investigation of communications with counsel beyond certain narrow limits?

MR. KOLMYKOV: From what I understand, there's no protective order in place yet.

MR. TROPP: The scheduling order in the case includes a prohibition of your investigation of communications with counsel, excepting limited

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circumstances. I assume it's your intention to live by the scheduling order in the case.

MR. KOLMYKOV: I do live by the scheduling order in the case. However, I'm interested in learning what documents did Dr. Gitlin review prior to forming his opinion as to the claim constructions as well as to prepare for this deposition.

MR. TROPP: Well, I have no objection to a question about what he reviewed in order to prepare his declaration or to testify. But the question is what did counsel provide you, and that comes awfully close to areas that are not permitted by the scheduling order.

So while it's not my intention to interfere with your questioning, I'm not sure that that question as you framed it is necessarily over the line, I do want your agreement that you're going to be living by the scheduling order and it's not your intention to inquire into communications with counsel.

MR. KOLMYKOV: I'm fine with that.

BY MR. KOLMYKOV:

Q. I'm only interested in technical papers.

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MR. KOLMYKOV: What was the last question I asked?

(Requested portion of record read.)

Q. Yeah, which patents did you review?

A. The one that comes to mind is the Betts '625.

Q. Did you read that patent in its entirety?

A. I read the patent. I didn't study it.

Q. When did you review this patent?

A. As I was preparing my declaration.

Q. Did you have any discussions with anyone outside -- apart from your attorneys -- regarding the subject matter of the '627 --

A. No.

Q. Let's refer to your CV, which starts on page D 0019.

Could you briefly describe your educational background?

A. I have a bachelor's degree from City College, 1964. A master's degree from Columbia University, and a doctor of science in engineering from Columbia University in 1969.

Q. I also see that you worked at Bell Labs

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for nearly 32 years.

A. Yes.

Q. Is that correct?

A. That's correct.

Q. I will go through -- strike that.

I understand you held several different positions at Bell Labs over these 32 years.

From 1969 to 1986 you were a director and supervisor and member of staff in advanced data communications; is that correct.

A. Yes, that's correct.

Q. And you state here that you were a coinventor of the pass band equalizer and many contributions to QAM systems, coded modulation, echo cancellation, V.32, V.34 modems.

What were these contributions to QAM systems?

A. The pass ban equalizer was the first equalizer that was matched to provide equalization for QAM transmission systems, and it is -- remains the standard equalizer for QAM systems today.

I built further enhancements to build fractionally spaced pass band equalizers, factionally spaced compliant pass band decision

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feedback equalizers, I invented imbedding Viterbi receivers, inside decision feedback equalizers.

We -- I did other patents on in-band modulation for use of data points to convey secondary channels.

I have several patents on echo -- various aspects of echo cancellation, and I was the manager and then the director in the development of the V.32 modems and the initial V.34 modems before I -- and it continued into 1987.

I also -- the work is closely linked, but had a different title.

Q. Thank you.

I also know from your CV that you worked at Globe Span, which is a -- was an AT&T spin-off?

A. I don't believe I said that. I helped create Globe Span. I didn't go with them. It says -- as it says in my CV -- helped create Globe Span.

I was the coinventor of DSL.

Q. So you helped create Globe Span, which later spun off of AT&T?

A. Yes.

Q. Do you know William Betts, the

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coinventor of the '627 by any chance?

A. I don't -- I may have met him, but I don't recall.

Q. Do you know Edwards Zuranski, who is also the coinventor of the '627?

A. No.

Q. While working on the -- from 1987 to 1992 at Bell Labs did you ever come across the disclosure of the '627 patent?

A. Not to my knowledge.

Q. From 1998 to 2001 I see your job description includes responsibility for standards.

What "standards" are you talking about in your declaration?

A. You're looking from '98 to 2001?

Q. Yes, that's correct.

MR. TROPP: I object to the form of the question.

A. The -- there were two jobs (indicating). I was -- out of Bell Labs' affiliation as the senior vice president, I was the CTO in the data networking unit.

So the types of standards -- these were data oriented standards -- IETF standards, the MPLS

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standards.

This was, at that point, above the physical layer. So these were networking standards. IETF, for example.

As well as getting involved in the cable modem business in -- from the layer 2 layer 3 CMTS, the head end.

And BLAST was something I had started in my '95/'98 work. That stands for Bell Labs Advanced Space Time Communication System.

And it is intended for wireless communications, wireless modems, using spacial domain and time domain, SMART antennas, as well as TDM techniques.

Q. So as I understand it, none of these standards dealt with data encoding?

A. At the physical layer.

Q. Yes.

A. When you say "data encoding" do you mean physical layer?

Q. Right, that's what I mean.

A. No. The BLAST was physical layer for wireless.

Q. For wireless.

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And none of those standards included digital television standards; is that correct?

A. I was not involved in the research on digital television.

Q. Are you familiar with digital television standards?

A. In a superficial way. Not in a detailed way.

Q. Could you elaborate on what do you mean by "superficial way" versus "detailed way"?

A. I know the broad technology that's used. But I'm not an expert in the details or the protocols.

Q. But you are familiar with the ATSC digital television standard?

A. I've read it.

Q. Are you familiar with the Grand Alliance?

A. I've heard the term. I knew people from Bell Labs and Lucent were involved in it. But I was not involved in it.

Q. From 1992 to 1995 you also worked on the DoCSIS standard; is that correct?

A. I was a vice president, and I had over

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100 people, and there were some people who reported to me who were involved in the DoCSIS standard. I was not personally involved. So I said "led and managed" in my resume. It's not personal contributions of mine.

Q. While working for these nonphysical layer standards, did you ever attend the Standards Setting Organization Meetings or technical meetings?

A. I certainly recall attending some IETF meetings for packet networking.

Q. You only attended the IETF?

A. In the time frame you suggested. I attended the -- many modem standards meetings from '69 certainly through '86.

Q. What were some of the modem standards that were involved -- that were related to the standard setting organization meetings that you attended?

A. CCITT Study Group 17.

Q. When you say "Study Group 17," what does that mean?

A. It was concerned with the V.32 modem, and then led to the V.34. Although I was less

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active in that. I at that time became a manager and director.

Q. What technology -- strike that.

Did the V.32 modem standard involve any trellis encoding?

A. Yes.

Q. Do you remember who else attended those meetings?

A. Well -- there were certainly people from all major modem companies.

I didn't attend every meeting. I attended selected ones.

Q. Did cable companies attend those meetings as well?

A. I couldn't say.

Q. Did broadcaster companies attend those meetings?

A. I don't have the list in front of me. But typically it was modem manufacturers, and PGTs from around the world.

Q. What are the PGTs? What do you mean "PGT"?

A. Post, telegraph and telephone.

So, for example, France Telecom would be

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PGT. It was government then, but now it's more private.

Q. When you attended those standard setting organization meetings did have an understanding that all parties who had any patents related to the standard were obligated to disclose those patents to the standard setting organization?

MR. TROPP: Before the witness answers that question, Counsel, I would like, I guess, to have some understanding of where you're going and what you view the scope of this deposition to be.

We had received an e-mail that suggested that the deposition was for the purpose of exploring Dr. Gitlin's declaration and issues related to the claim construction issues therein, as well as bias.

And while I certainly will not prevent you from exploring his CV to the extent appropriate for this deposition, it does seem to me as though you're now using the CV as a means to inquire about subjects that are rather far afield from the areas you indicated you were intending to explore in the deposition.

MR. KOLMYKOV: I do agree that this

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deposition is limited to claim construction and the declaration of Dr. Gitlin. The declaration does talk about standards and his involvement in the standards. But that is the last question I will ask about the standards.

MR. TROPP: Well, for the record, the declaration doesn't talk about standards. The attached CV does. And of course the witness has vast experience beyond that which is the subject of his declaration.

But on your representation that that's the last question -- can I hear it back.

(Requested portion of record read.)

MR. TROPP: If that's your last question, I won't interfere.

A. Which meetings are you referring to?

Q. Such as, for example, CCITT meetings.

A. Different groups had different -- different standards, bodies had different policies. It's a long time ago.

What I did, I always spoke to my attorney and said, if we're making a contribution, what do we do, and I followed the attorney's advice.

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Q. Okay, thank you.

MR. KOLMYKOV: The reason I'm asking about it also, Counsel, is because Dr. Gitlin does have over 40 -- 47-something patents related to all kinds of standards, and he would be aware of whether he needs to disclose something and whether he doesn't need to disclose this contribution.

MR. TROPP: Assuming you're right, that he would know, and would be happy to talk at some further deposition about some of those issues, it seems to me to be beyond the scope of what we're here for.

On your representation that was the last question, I certainly didn't interrupt or prevent him from answering it. So I'm happy to move on.

MR. KOLMYKOV: I understand your position.

BY MR. KOLMYKOV:

Q. Dr. Gitlin, what is your current position?

A. Right now I am in the process of becoming -- as my resume says -- a professor at University of South Florida in Tampa.

I'm also CTO for Hammerhead Systems in

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Mountain View, California.

Q. I also understand you do consulting.

A. I do consulting.

Q. You've already identified other litigations that you've consulted in, and that includes the Interdigital ITC litigation that's going on right now?

A. Yes.

Q. What is your hourly rate?

A. It depends.

Q. What is your hourly rate for this deposition?

A. As I recall, I think it's 575 per hour.

Q. And what is your hourly rate for drafting this declaration (indicating)?

A. That's my hourly rate.

Q. You mentioned your contributions to QAM systems.

What is a "QAM"?

A. The "QAM" stands for quadrature amplitude modulation.

Q. And what is modulation?

A. What is modulation or what is a quadrature amplitude modulation?

- Gitlin -
Q. What is modulation in general?
A. That's, you know, a very general term. So it can mean many, many things, and I prefer to answer in a specific context as opposed to giving a dictionary definition of "modulation," or trying to give a dictionary definition.
Q. Wouldn't it be fair to say that modulation is changing one or more characteristics of a carrier wave to transmit data?
A. That's not a complete definition.
Q. How would you complete this definition?
A. You left out the case of an analog modulation, which is a continuous signal. It's not discrete data.
Q. So how would you define "analog modulation"?
A. Well, the analog modulation is when the source information is analog, and you want to transmit it over a medium that requires some modulation to efficiently transmit the information.
Q. Isn't it correct to say that when a system modulates a signal, an analog signal, it changes its wave characteristics?
A. I was talking about the basic signal was

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analog. And, for example, modulating a sine wave. So you can have an analog signal in general. Just, you open up a textbook, you can get a book on analog communications.
So you would have an analog signal, like a radio signal, modulates carrier, amplitude modulated or frequency modulated.
Q. Is there any other kind of modulations?
A. You can modulate time, space, codes, positions. There's plurality. There's many, many things you can modulate. In general. You asked me an open-ended question, so...
Q. So the only way digital modulation differs from analog modulation is because the input is a discrete data as opposed to a continuous wave?
A. That's the most significant way. There might be others, but that's the most significant.
Q. And sitting here today, you can't think of any other difference?
A. Between what?
Q. Between digital modulation and analog modulation.
A. The high level definition of analog modulation is that the source signal is analog.

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For example, speech. Analog speech.
And digital modulation deals with the source that is in digital form.
Q. So when a system modulates -- strike that.
When the system needs to transmit a speech signal and it wants to modulate it in amplitude, what characteristic of that signal would it change?
A. Can you rephrase the question?
Q. You don't understand the question I asked?
A. It's -- I think -- I want to be sure I understand the difference between the source and the wave form that you're modulating. You were not clear to me.
Q. Let's assume the source is an analog continuous wave and you want to transmit speech, a speech signal.
How would you modulate it?
A. You can modulate the amplitude as an AM radio; you could modulate the frequency as an FM radio, for example.
Q. So when you're modulating an amplitude,

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what are you changing in the source signal?
A. You're changing the amplitude of the source.
Q. Is that the only parameter that you're changing of the source?
A. For amplitude modulation?
Q. Yes, for amplitude modulation.
A. Well, you're generally concerned about things, about DC levels, so you're probably at a constant to the speech signals, and you might have a constant to keep the carrier wave above zero, and then you add that and modulate it.
But there are many, many variations on that.
I mean, you could -- you can modulate the cosine wave and you can modulate a sine wave with information.
Q. So when somebody modulates a sine wave, for instance, in amplitude, is it fair to say that the amplitude of that sine wave is being changed and not its frequency or its phase?
A. If you modulate both cosine and sine waves, then you effectively are changing the amplitude as well as the phase.

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Q. We will get to that.
But let's say there's one signal, one continuous wave, and your — and it's one sine wave, and we're modulating this wave simply in amplitude.
Which parameter are you changing?
A. The amplitude.
Q. And if you're modulating simply in phase, which parameter are you changing?
A. The phase.
Q. Now, let's get back to the concept that you've just introduced.
If you have two waves, sine and cosine, how do these waves differ?
A. One's a sine and one is a cosine.
Q. In terms of phase, how are they different?
A. They are 90 degrees out of phase.
Q. When would you ever use both waves to transmit data?
A. Are you talking about digital data?
Q. Let's assume from now on we're dealing with digital data.
A. Could you just ask the question again?

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Q. Can you think of a modulation technique that uses both waves, sine and cosine, that transmits data?
A. As I said before, QAM modulates both the cosine and the sine.
Q. Could you elaborate a little bit on how both waves are modulated and then are used to transmit the data signal?
A. In the most straightforward case, you modulate the amplitude of the cosine wave, but you probably first pass the source bits through a shaping filter. So you have a confined band with a signal.
And you would pass another set of bits through another shaping filter and modulate the sine wave.
And so that composite signal is referred to as quadrature amplitude modulation.
Q. When you say "composite signal," are the two waves that are 90 degrees out of phase added together before they are transmitted?
A. Generally, yes.
Q. So how does QAM modulation differ from digital amplitude modulation?

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A. It -- it differs -- certainly that you're modulating concurrently both the cosine and sine, the amplitude of each.
And, thus, effectively the amplitude and the phase, if you looked at the modulation of -- at each modulation instant time, if you're looking at how you're modulating the cosine and sine and think of that as a two-coordinate vector, or X/Y coordinate, you have a signal point.
So you have a -- more flexibility.
Q. So in essence you are -- before you're transmitting a signal you're changing its amplitude and you're changing its phase?
A. One interpretation of the simultaneous modulation of the cosine and sine is that you change it to polar coordinates so you have an amplitude and the phase. So they are completely equivalent. You can modulate each of the axes and changing to cartesian to polar coordinates you have an amplitude and a phase.
Q. In cartesian — strike that.
Does it matter in which coordinates you are operating?
A. I'm not sure. "Does it matter" is a

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very general concept.
Q. In terms of practical implementations of the system, does it matter --
A. I think, you know -- things tend to matter when you're pushing the technology speeds. There might be some things that are easier to do in cartesian versus polar coordinates.
But when you're in a region where you're using digital signal processors, designers will make the choices how they feel it's most convenient to operate. It may be based upon the technology that they have at hand for implementation.
Q. So the choice of coordinates -- coordinate systems is implementation-specific?
A. Well, within the QAM, whether they use cartesian or polar coordinates, I would say it's a -- it's an implementation consideration.
But I just want to make sure the discussion is confined to QAM. Because you could have -- there could be other considerations. So I'm assuming -- I gave my answer in the context of QAM.
Q. Okay.
When a system only changes the amplitude

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of the carrier wave, would it be fair to say that that's a one-dimensional modulation?
A. Are we talking about coded or uncoded systems?
Q. Let's talk about both.
A. I'm sorry, I could hardly hear.
Q. In the uncoded system first.
A. Could you please repeat the question.
MR. TROPP: Why don't we take a second.
MR. JUISTER: Can we take a break? We've been going for about an hour.
MR. KOLMYKOV: Sure.
MR. TROPP: We're going to go off the record and take a break.
MR. KOLMYKOV: The time is 11 a.m., and we're going off the record.
(A recess was taken.)
THE VIDEO OPERATOR: The time is 11:18 a.m., and we're back on the record.
BY MR. KOLMYKOV:
Q. We talked about analog modulation and digital modulation.
And my last question to you was: One parameter of the way it's changed, are you

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modulating the wave in one dimension?
A. I'll repeat my question: Are you talking about a coded system or an uncoded system?
Q. What's the difference between a coded system and an uncoded system?
A. The dimensionality referring to how you're going to process the signal at both the transmitter and, equally importantly, the receiver.
So if you have a dependency between more than one dimension -- for example, in a two-dimensional signal you process both dimensions at the transmitter to do the transmitter processing and you process both dimensions at the receiver to do the receiver processing.
If you have more than two dimensions, that same argument applies. The same logic applies.
Q. Could you give me an example of a two-dimensional modulation?
A. Yes.
QAM.
Q. Can you give me an example of a one-dimensional modulation?
A. This (inaudible) side band.

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Q. Would amplitude modulation be a one-dimensional modulation in a coded system?
A. In a coded system?
Q. Yes.
A. We have a finite number of words in the English language, and it becomes very specific to the system. In coding you're -- you're establishing a dependency between the various points, signal points.
So the modulation itself may be a one-dimensional modulation. But the -- you modulate a carrier wave with an amplitude, but the dimensionality of the signal -- composite signal will depend upon the type of encoding that you have.
Q. What are the different types of encoding that would affect the dimensionality of the signal?
A. Well, the most -- generally, you could have block codes, convolution of codes, and trellis codes form in the class of convolutional codes, but they are most celebrated for the fact that they combine the modulation and coding.
Q. But you do agree there is such a concept as one-dimensional modulation?

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A. It's context-dependent.
Generally I prefer to say one-dimensional modulation for an uncoded system is clear.
Q. Would amplitude modulation for an uncoded system be a one-dimensional modulation?
A. Yes, it would.
Q. Would phase modulation also be a one-dimensional modulation?
MR. TROPP: Objection to form.
A. Generally, I think of phase modulation as a two-dimensional modulation. Because you're equivalently modulating every point on a phase, or a circle, really as an in-phase and quadrature point.
So I think of that as -- within the QAM family, as two-dimensional modulation.
Q. So you refer to a phase modulation such as PSK modulation as two-dimensional modulation?
A. I myself think of it as a special form of QAM where you restrict the X and Y coordinates so that the sum of the squares of the X and Y is a constant. It gives you a point on a circle. And that may -- that's the way I think of it.

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Q. But do you agree that other people in New York would refer to it -- may refer to it as one-dimensional?
A. I wouldn't necessarily agree.
Q. You just said that's how you think of it.
A. Right.
Q. But others may think otherwise?
MR. TROPP: Objection.
Q. In New York?
A. Frankly, I don't recall anyone saying the one-dimensional phase modulation. It's something that I'm not familiar with hearing.
Q. So if you're changing -- let's refer to paragraph 20 on page D 0011.
(The witness complies.)
MR. TROPP: For the record, you're on paragraph 20 of the declaration that's been marked as Exhibit 1?
MR. KOLMYKOV: Yes.
Q. You're stating that both dimensions of the carrier wave, I and Q, are modulated to generate one signal point. So you're stating that I and Q are both changed?

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A. In paragraph 20?
Q. Yes.
A. That's what I said.
Q. Therefore, a signal point is two-dimensional?
A. In the context of this -- this is a -- I'm talking about trellis coding and multi-dimensional trellis coding, and I said the TCM techniques described above are referred to as two-dimensional, 2D, since in each signaling intervals both dimensions of the carrier wave, I and Q, modulate to generate one signal.
Q. Is it possible to have a one-dimensional signal point outside of your declaration (indicating)?
A. Not in the context of the patent? In general?
Q. In general.
A. So, yes, you could have a one-dimensional signal point.
Q. But your declaration is talking about a two-dimensional modulation, because you're changing I and Q components, and that two-dimensional modulation is phase modulation known as 8-PSK?

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A. In paragraph 20 I give an example using 8-PSK signal constellation. That's two-dimensional modulation.
Q. Okay.
Isn't it true that in phase modulation you're only changing the phase parameter of the wave?
MR. TROPP: Objection.
A. In -- in the context of QAM, which has as its basis cartesian coordinates, you are changing both coordinates, X and Y.
Q. Let's talk about outside the QAM concept.
When you change the phase of a carrier wave, you're changing only one parameter of the wave and, therefore, it's one-dimensional?
A. I -- I don't agree.
The dimensionality to me refers to how I would process, as I said before, the transmitter and the receiver.
If, as is in commercial practice, people use I and Q systems, for me to produce an 8-PSK signal, I would modulate the X component, modulate the Y component, transmit the signal.

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If it's a PSK signal, it's such that the sum of the squares of the two coordinates is a constant. That's the amplitude of the signal.
Similarly, at the receiver I would process the received in phase or received quadrature to determine which of the transmitted -- which of the signal points was transmitted.
That's the way it's commonly done.
Q. Let's look at your PSK constellation document on page D 0003 --
A. 3?
Q. -- of your declaration.
To move from point P1 to point P2 which characteristic of a wave are you changing?
A. It depends how you view it. If you view it in the I and Q, you're changing the I and you're changing the Q.
If you were going in polar coordinates, you're changing the angle or phase.
Q. So polar coordinates you're only changing one parameter, and that is the N?
A. Yes. But, you know, in practice -- if you're in the domain of QAM modulation, all of the systems I'm familiar with use the cartesian

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coordinates.
Q. In your practice engineers use cartesian coordinates.
However, is it possible to use polar coordinates to represent phase modulation?
A. In principle, yes.
Q. When you're in the cartesian coordinates, and let's say you're at point P1, which component, I or the Q, represent the phase?
A. The phase is computed from the I and the
Q. It's simply the angle that if you draw a vector from the origin to P1, the phase relative to, you know -- would be the angle.
Q. So for phase modulation you're only changing the angle?
A. In 8-PSK, you have one of eight phases. That is selected at each signaling instant.
Q. And so the phase is the only parameter that is changed from one point to another?
A. If you're viewing this in polar coordinates.
Q. Okay.
A. But people view this in QAM because signal processing both in the transmitter and the

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receiver is most conveniently, expeditiously done in cartesian coordinates.
Q. What do you mean by "most expeditiously"? What is so expeditious about using cartesian coordinates versus polar coordinates?
A. When -- when the signal is distorted through transmission, you're going to have to do receiver processing. And by using cartesian coordinates you have the benefit of using operations whose mathematical forms and algorithms are well understood, many are explained and done in terms of cartesian coordinates.
And there might be some receivers that operate on polar coordinates for complex systems when you're dealing at the receiver. But I'm not familiar with -- with those, and it seems that that's not a natural way to -- it's not a natural way to process the signal.
Q. What are the unnatural ways to process the signal?
A. A natural way is to process using a QAM, because you process the signal and you do processing of the vector, the I and Q. And in many receivers, in almost all I'm familiar with, the

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operations are defined in terms of those coordinates. We have complex things like equalization, echo cancellation, decoding, in terms that are defined in terms of I and Q.
Q. I'm sorry --
A. Either independently or jointly as a vector.
Whereas the amplitude -- remember, you transmit something on a circle. When it's received it's distorted; it's no longer on a circle.
So most naturally then you have to introduce the notion of an amplitude, because you're going to receive a signal that now has a phase, but the amplitude you can't control.
So the processing that -- we have a lot of processing that's based upon linear systems, and those are the most natural and compatible with I and Q representation.
Q. So in one implementation, one compatible way to represent phase modulation is in cartesian coordinates having I and Q as the two axes?
A. You asked me a question?
Q. Yes.
A. Can you repeat it?

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MR. KOLMYKOV: Can you read that back.
(Requested portion of record read.)
A. That to me, that's the preferred way, and that's the way it's generally done, although there may be exceptions. That's the way it's done.
Q. Do you know of any exceptions?
A. For a -- well, for a QAM system that's the way it's done.
Q. Let's refer to the declaration on page D 0029.
(The witness complies.)
Q. It would be the reference -- I'm sorry, it would be the Ungerboek reference.
So in the figure 1, you see that it illustrates amplitude modulation and the points are on one line.
(The witness reads document.)
MR. TROPP: Is there a question?
Q. Well, I just wanted your confirmation --
A. About what?
Q. -- that you see the illustration.
A. Figure 1?
Q. Yes. Figure 1.
A. I'm looking at it.

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Q. Do you agree that this is a one-dimensional modulation that's illustrated?
A. For --
Q. For the ampli --
A. As the caption says, the upper left is labeled amplitude modulation for 2-AM, 4-AM, 8-AM, 16-AM.
It's 2-AM, not the time. It's 2 amplitude modulation.
Yes.
Q. I understand what Mr. Ungerboek wrote. But I'm asking your opinion whether this is amplitude modulation, whether this amplitude modulation is one-dimensional modulation?
A. I would agree that's one-dimensional modulation.
Q. Why is it one-dimensional modulation?
A. He's talking about an uncoded system here, and he's modulating the amplitude.
Q. And because he's modulating just one parameter of the wave, such as amplitude, it is one-dimensional?
A. Well, the situation is different.
You see, if you look at what he calls

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phase modulation -- you asked me a question.
If you see what he says here, he's modulating 4-PSK, 8-PSK, 16-PSK, and he refers to that as two-dimensional phase modulation.
Q. Okay.
But my question is: The reason amplitude modulation is called one-dimensional amplitude modulation is because you're only changing one parameter of the wave?
A. Yes. The undisturbed frame of reference here is that you're dealing with QAM systems. That's the reference for this discussion.
Q. Which discussion?
A. His paper.
Q. His paper -- doesn't his paper lay out different modulation techniques in figure 1?
(The witness reviews document.)
A. It's within the frame -- in my opinion, it's within the frame of reference of QAM modulation, or combined amplitude and phase modulation, or in-phase quadrature modulation.
Q. Where do you see --
A. When he says two-dimensional, I interpret that as QAM.

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Q. Aren't there any other types of two-dimensional modulations?
A. Amplitude and phase.
Q. Apart from amplitude and phase, are there other types of two-dimensional modulations?
A. Well, you could -- it depends on the context.
Q. Theoretically, could there be other ways to modulate the signal, apart from the combination of amplitude and phase?
A. You could pick -- there's lots of coordinates. You might -- it's a question of in this time when he wrote this what were people working with. There might be other dimensions that people might consider today. But in the time frame that this was written (indicating), when people talked about two-dimensional, the pictures that he shows and the words he uses are understood to be QAM system.
Q. Why do you think this reference is in the context of QAM systems? Isn't it true that this reference doesn't even mention the word "QAM" anywhere?
A. Well, he refers to a -- what was going

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on in the ITU, the CCITT for new high-speed voice band modems. He was an active participant.
These were all QAM-based systems.
And I would say in my experience, from the late seventies to -- almost today -- almost all high-performance digital communication systems are QAM-based. Almost all.
Q. Is there another way to modulate phase and amplitude, apart from the QAM method?
A. I'm not sure I understand the question.
Q. We established that QAM is separating the digital data into two components, and each of those components is applied to a sine wave and a cosine wave, which are 90 degrees apart?
A. Yes.
Q. What if we used only one wave and used that wave to modulate phase and amplitude instead of splitting it up into two waves: Would it be possible?
A. Well, you know, by algebra, if you modulated the sine and cosine, there's an identity where you take the -- you could write it as one sine of sort of wave, where the amplitude is the square root of the sum of the squares of the

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in-phase quadrature, and the angle is the sine wave is the arc tangent of the ratio of the in-phase to quadrature term.
So just using algebra, you can go back and forth between the I and Q and polar coordinates.
Q. In other words, you don't have to call it QAM if you're modulating the phase and amplitude of the signal?
A. Well, for -- in all my experience it was understood at this point in time when you modulate a signal in the X/Y plane you can have many different types of signal constellations, which is the collection of signal points.
Ungerboek shows several of them. Other people. In our book we show many of them. And it's understood that that's what you mean.
I don't know of anyone who did signal processing in terms of noncartesian coordinates in high-performance digital communication systems.
Q. Can we agree that digital signals can be modulated in one dimension?
A. Ungerboek gives a example of amplitude modulation.

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Q. And this example illustrates that because amplitude has changed and nothing else that's why it's one-dimensional?
A. You're modulating the amplitude. That's the one dimension that you're modulating.
Q. On the other hand, when digital signals are modulated in two dimensions, you're changing two characteristics of the wave, such as phase and amplitude?
A. Yeah -- within the construct of in-phase and quadrature modulation you could have an arbitrary signal constellation.
Q. But you're changing two parameters?
A. You're changing the in-phase and the quadrature coordinate. That's the frame of reference, the coordinate system you're talking about.
Q. If we are talking about in polar coordinates, you're changing phase and amplitude, you're changing two characteristics of the wave?
A. There's a complete equivalence between X and Y and the polar coordinates.
Q. Right. So it doesn't matter which mathematical representation you use, you're still

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changing two characteristics?
A. To the best of my knowledge, no one uses a polar coordinate system to deal with these high performance digital communication systems.
Q. But that's the question I asked. I asked if two components are changed of the carrier wave, then it's a two-dimensional modulation?
A. If -- if relative to the cartesian coordinates you changed two coordinates, it's a two-dimensional system.
Q. What about relative to polar coordinates; isn't it also a two-dimensional system?
A. If you do what?
Q. If you change phase and amplitude.
A. You would change -- it's just -- people don't talk about the dimensionality in a high performance system using polar coordinates. So, I mean -- I'm just going to comment on that. It's not the words that I would use. I'm not familiar with anyone using those words.
Q. Okay. In cartesian coordinates, when you change phase and amplitude you're dealing with a two-dimensional system?

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A. As Ungerboek points out, even if you change the phase it's referred to as a two-dimensional system.
Q. And that's because you're changing the I and the Q?
A. Yes.
Q. Okay.
MR. KOLMYKOV: How are we doing on tape?
THE VIDEO OPERATOR: Two minutes.
MR. KOLMYKOV: I'm going to start this line of questioning, and then we'll change the tape.
Q. In figure 1 you mention these are the signal points that are illustrated on a constellation, different ways of representing signal points on a constellation?
A. Are you reading from somewhere?
Q. Just looking at figure 1.
(The witness reviews document.)
Q. Just illustrates a variety of constellations.
A. Yes.
Q. What is a signal point?
MR. TROPP: Objection.

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A. So a signal point is a point in this two-dimensional space, so it has X and Y coordinates.

Q. What about a point in amplitude modulation figure?

A. In Ungerboek's paper.

Q. Yes, in Ungerboek's paper.

A. That is one-dimensional, so it has amplitude.

Q. So Ungerboek's paper illustrates a one-dimensional signal point in figure 1, under "Amplitude Modulation"?

A. Figure 1, the upper left-hand corner, is an example of amplitude modulation.

Q. And the point on that constellation is a one-dimensional signal point?

A. Yes.

MR. KOLMYKOV: Could we --

THE VIDEO OPERATOR: This completes Tape Number 1. The time is 11:52 a.m., and we're going off the record.

(A recess was taken.)

THE VIDEO OPERATOR: This is Tape Number 2. The time is 12:00 p.m., and we're back on the

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record.

BY MR. KOLMYKOV:

Q. So we can agree there is such a thing as a one-dimensional signal point in theory?

A. Yes. I mean, amplitude modulation is a -- the example of it.

Q. And can we agree that a signal point represents some sort of a value?

A. It depends on the context.

Q. Let's say in the context of one-dimensional constellation such as amplitude modulation.

A. As the example in Ungerboek's paper of amplitude modulation, yes, that's one-dimensional.

Q. But it represents one value?

A. Yes.

Q. And in let's say QAM modulation, he would represent two values?

A. I mean, a signal point has two components in QAM systems. Or in two-dimensional systems.

Q. What are those two components?

A. The X -- the in-phase and quadrature component.

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Q. Okay.

What is a signaling interval?

A. Signaling interval is the period or the time at which -- time between successive modulations of the channel.

Q. Is it true that a signal point is always transmitted in one signaling interval?

A. In -- if you use a two-dimensional QAM system, you transmit the QAM signal point in one signaling interval.

Q. What if he used something other than QAM? Let's say VSB?

A. The signaling interval is the -- one over the frequency with which you modulate the carrier wave.

Q. But you're still sending one signal point during this one-signaling interval, whether it's -- whether you use a QAM modulation or a VSB modulation or amplitude modulation or phase modulation?

A. In a signaling interval you transmit one signal point.

Q. So we can agree that a signal point is a value that may have two components, the I and the

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Q, that is transmitted over one signaling interval?

MR. TROPP: Objection.

A. What type of system are we talking about?

Q. Any system.

A. Are we talking relative to the patent at issue, or are you just having a general discussion?

Q. We're having just a general discussion.

A. Within the construct of a two-dimensional system, a signal point is transmitted -- a two-dimensional signal point is transmitted at every signaling interval.

Q. What if you don't use a two-dimensional constellation? What if you use a one-dimensional constellation, such as amplitude modulation, which we established was a one-dimensional constellation?

A. I didn't hear a question.

Q. In that case, a signal point is represented by one value because the points are on the line.

A. If you use a one-dimensional system, then the signal point is -- would be as described in Ungerboek's figure 1 in the upper left-hand

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corner.

Q. One value?

A. You transmit one signal point. It's one-dimensional.

Q. So you transmit one value over one signaling interval?

A. Yes.

Q. What is a "signal point constellation"?

A. A signal point constellation generally refers to the context of an in-phase and quadrature system where you modulate both the in-phase and quadrature -- that is, the cosine and sine -- and the constellation represents the set of points, signal points, that you're going to transmit. That's the alphabet, so to speak, of signal points.

And these are -- in these systems they are two-dimensional. Each point in the constellation is a two-dimensional signal point.

Q. In the QAM system?

A. In the two-dimensional system.

Q. In the two-dimensional system a signal point is two-dimensional?

A. Yes.

Q. So a signal point corresponds to a

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signal mapped to a constellation?

A. In what system are we talking -- QAM system?

Q. Just generally, any system. It's a signal that is mapped to a constellation?

A. What I would say is you modulate the I and Q, you select one of the points, and the X value modulates the cosine wave, and the Y value modulates the sine wave.

This diagram is over-simplified. The digital modulation goes through a shaping filter to restrict the bandwidth, and then you modulate either the cosine, or, with the other coordinate you modulate the sine wave.

That's how it's done.

Q. Before you're actually applying signal points to a wave, you're mapping that signal point onto a constellation?

A. The signal constellation is comprised of signal points, so the constellation is the alphabet or the set of signal points.

Q. So we've established there's an alphabet of signal points.

So if you receive a signal point, the

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next step would be to map it onto this alphabet?

MR. TROPP: Objection.

A. It depends upon the system. In an uncoded system, simple -- not in the context of the sophisticated systems that we're talking about that Ungerboek is talking about or the patent is addressing, you receive processing, depending upon what form of processing was done at the transmitter, relative to, for example, if you use trellis-coded modulation, what sort of impairments you expected in the channel.

Q. Isn't it correct that at some point during processing a signal point is mapped onto a constellation?

A. I'm not sure -- are you talking about the transmitter or the receiver?

Q. In the transmitter.

A. I'm not sure what you mean by "mapped onto a constellation."

Q. We've established we have an alphabet of signal points. To choose one of the signal points that are allowed, you're mapping the received signal point onto the allowed set in the alphabet.

MR. TROPP: Objection. I don't know if

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you want me to say anything further than that or not. But I might be happy to help you a little bit there.

MR. KOLMYKOV: I know what I'm doing. If he doesn't understand the question, he can ask me.

MR. TROPP: That's fine. I understand. So respectfully, then I object, because I think that the question is problematic.

A. You started out talking about transmitter and then you put receiver, so I don't understand that.

Q. I apologize.

MR. TROPP: And that was my objection.

Q. Let's talk about the receiver.

In the receiver, the received point is mapped onto a constellation?

A. Are we talking about an uncoded system or a coded system?

Q. Either one. There is some mapping going on.

A. Well, mapping -- I would prefer to say if you -- mapping includes a tremendous amount of signal processing. You receive signal points

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depending upon the level of processing.
So, for example, in the Betts patent he's dealing with, for example, a four-dimensional system. So you would get at least -- receive signals from those four dimensions, process it through the trellis decoder, let's say Viterbi algorithm, and at some point you will then produce the best estimates of the transmitted bits.
So I wouldn't call that a mapping.
A mapping -- a mapping in my language has more of a memory-less aspect.
Q. Okay, let's call it represented.
Can a signal point be represented on a one-dimensional constellation, such as figure 1 of Ungerboek's reference?
MR. TROPP: Objection.
A. Are we talking about transmitter?
Q. Yes. In the transmitter instance.
A. As per the example by Ungerboek, he shows amplitude modulation.
And, for example, in the four amplitude modulation case you transmit one of the four signal points which are depicted as circles. That's your alphabet.

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Q. Okay. So this one signal point, let's say in the 4-AM, is one out of four choices?
A. Was that a question?
Q. Yes.
A. There are four possibilities. You select one of them.
Q. What is the difference between a one-dimensional signal point and a two-dimensional signal point?
A. In a two-dimensional signal point you have two components, an in-phase and quadrature signal point.
In a one-dimensional signal point you have one component; for example, the amplitude.
Q. Is there any advantage to using a one-dimensional signal point versus a two-dimensional signal point?
A. The pendulum swings the other way. There's lots of advantages for increasing the dimensionality of a signal point. Certainly two-dimensional signal points -- signal constellations have more flexibility and more advantages than one-dimensional.
Q. What are those advantages?

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A. Well, you get, for a given received power -- sorry, given transmitted power you can generally get a better performance and error rate, even in uncoded systems, going from two-dimensional to one-dimensional.
Q. By increasing -- by decreasing the error rate you mean the coding gain has increased?
A. I was talking about a simple uncoded system.
So for a given transmitted signal power you have a lower error rate in general with the QAM system, the two-dimensional system, than a one-dimensional system.
Q. Why is that?
A. Just that you have the ability to -- you have more degrees of freedom in two-dimensionals than you have in one to place the points in a way that can give you more separation against noise.
Q. Well, a two-dimensional point carries two values; is that correct?
A. Yes.
Q. A one-dimensional point carries one value?
A. Right.

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Q. Can't you just send two one-dimensional signal points instead of two -- one two-dimensional signal points?
A. If you want to do -- this will be a long answer.
If you wanted -- when you have one-dimensional and you want to think of it now in sending a succession of one-dimensional, then it restricts you to having -- if you look at it in two dimensions -- a square signal constellation.
There may be reasons where you don't want a square signal constellation, as, for example, Ungerboek shows in his figure at the right-hand side, "Amplitude/Phase Modulation," where he has constellations where he deletes or expurgates the points of largest magnitude.
So you can get reduced transmitted power.
There's another much more subtle advantage for using QAM versus one-dimensional. This was recognized by several people in the -- myself included -- in the mid-eighties. And we devote a good section of -- a good portion of I think chapter 5 in our book to this.

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So this is a very idealized system. But when you go to build a real system, whether you use one-dimensional modulation or two-dimensional modulation, you find that there are other attributes, like carrier phase recovery, that you need to do. And it's been well-known and proven that QAM systems are much more robust in the ability to recover the carrier phase directly from the information bearing signal, whereas one-dimensional system, such as VSB, cannot do that.

In order to do that you have to introduce the notion of pilot tone.

And in order to make that system reliable, you generally put as much power in a pilot tone as you put in the modulated signal. And therefore you immediately take a 3 DB penalty in received power.

Moreover, what we found from our experiments in this system, when you put a pilot tone in, if you're in the presence of harmonics in the channel, you can also get harmonics generated from that pilot tone into the data band, further degrading performance.

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So it became the conviction of many people, myself included, that two-dimensional modulation had very real, practical advantages in terms of the carrier phase recovery and coherence detection, that I just described, in addition to giving you more flexibility by being able to build constellations in two dimensions, such as the one Ungerboek shows with a cross, which are not square.

Q. So you agree that it is possible to design a system that sends two one-dimensional signal points versus one two-dimensional signal points?

A. It's possible, but nobody -- nobody was doing this in the commercial space of modems after certainly 1980. It was not done because of the reasons I said. You could do it. But it was not the practice. People understood the superiority of QAM systems.

Q. So you can't think of any applications where a one-dimensional system has been implemented since 1980?

A. The only one I can think of is the ATSE standard.

Q. But your opinion is that is inefficient?

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A. I'm not an expert in that. I think there were other issues related to range, and they use a pilot tone.

I recall there was a debate between QAM and VSB and, as these debates go, VSB won. And that's a different circumstance than the wire line systems in the context of Ungerboek had been dealing with, and the Betts' patent addresses.

I would say, to be fair, that's about the only system, commercial system, I know that could be called a one-dimensional system since the -- around 1980.

Q. So since ATSE does use a one-dimensional system, it is possible to use a one-dimensional system?

A. Yes.

Q. Even though according to your opinion it's not as good as the QAM?

A. In the context of the environments that I'm intimately familiar with. I'm not an expert on over-the-air television transmission.

Q. Can trellis encoding be implemented with one-dimensional signals?

A. Yes. Yes.

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MR. KOLMYKOV: Okay. Let's mark another exhibit, the 5,243,627 patent. I will call it the '627 patent.

MR. TROPP: Would you agree, so that our record is clear, that you have in fact occasionally referred to it as the '627 patent and that's what we meant by this patent?

MR. KOLMYKOV: Yes, that's what we meant.

(Gitlin Exhibit 2 marked for identification, 5,243,627 patent.)

MR. TROPP: If you're about to change gears entirely, would now be a better time to take a break, or would you prefer to press on?

MR. KOLMYKOV: It is a change in gears. I don't know about entire --

MR. TROPP: It's your deposition.

MR. KOLMYKOV: I will ask the deponent. Are you okay with continuing?

THE WITNESS: About how long would you expect to go?

MR. KOLMYKOV: Let's say 20 minutes.

THE WITNESS: 20 minutes is okay.

BY MR. KOLMYKOV:

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Q. Have you seen this document before?

A. The patents -- the '627 patent?

Q. The '627 patent.

A. Yes.

Q. In your opinion, what is the problem in the art that the '627 patent resolved?

MR. TROPP: Objection.

(The witness reviews document.)

A. The -- the assertion or the claim in the '627 patent is that it provides a signal point interleaver for multi-dimensional -- for example, four-dimensional channel symbols, where the -- you have pairs -- in that example, pairs of signal points that are produced, that are -- by one state transition.

Q. Isn't it correct --

MR. TROPP: Can he finish his answer?

MR. KOLMYKOV: I'm sorry.

A. The inventor proposes a signal point interleaving technique -- in his words -- causes the constituent signal points -- that is, the points which are produced from this -- of this one-state transition -- to be non-adjacent as they traverse the channel.

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So he builds upon a previous -- or builds upon the interleaving technique that he described previously.

And here he makes it very specific to 2N-dimensional signaling and greater than one, and he proposes a signal point interleaver. So...

Q. Isn't it correct to say that the '627 patent resolves a problem common in the art, what is known as an occurrence of burst errors?

MR. TROPP: Objection.

A. That problem is well recognized in the art. Dealing with burst errors, there is -- there's a long history of interleaving techniques to compensate for burst errors. Going back, for example, one of the references I cited was from Gallager's textbook. He refers to it as interlacing, as opposed to interleaving.

And in the '625 from Betts, Betts proposes a set of, in his language, a plurality of trellis-coders to provide an interleaving of the outputs.

So the problem of dealing with burst errors has been a well recognized problem, and, as I said in my declaration, the claim is that he

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provides a means of separating adjacent -- time adjacent points that are produced by a multi-dimensional code.

Q. So you would agree that the '627 resolves the problem of burst errors different from the '625 patent?

A. I haven't studied the '625 patent in great detail. It seems what I do observe is when I look at the '625 patent it's very generic, and I -- I really don't have, at this point, other than saying that '625 patent is a generic technique for taking art -- let's say as proposed by Gallager for general interleaving, in Gallager's language interlacing, and extending that art for trellis encoding.

But the '625 is a fairly generic patent, and I haven't been asked to comment on the distinction between '625 and '627. So I really don't have, you know, an opinion at this point in time.

Q. Okay.

You stated that you did look at the '625 patent.

A. Yes.

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Q. And the '625 patent does disclose an interleaving technique of some sort?

A. Yes.

Q. The '627 patent also discloses an interleaving technique of another sort?

A. Title of the patent is "Signal Point Interleaving Technique."

Q. And the '627 patent interleaves data differently from the '625 patent?

A. It's not clear to me the -- I haven't studied detailed claims of the '625. It's more generic than the '627 patent.

Q. You mentioned that trellis encoding could be implemented with one-dimensional signal points; is that correct?

A. Yes.

Q. The '627 patent refers to 2N-dimensional signal points.

Do you see that?

A. Where are you looking?

Q. Let's say column 2, figure -- line 53 -- 54.

A. Yes.

Q. The 2N-dimensional signaling scheme

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that's referred to in the specification of the '627 patent means that each signal point is two-dimensional; is that correct?
A. The signal point is -- each signal point is two-dimensional, yeah.
Q. Does the '627 patent disclose the dimensionality of a signal point anywhere in the specification?
(The witness reads document.)
A. Can you repeat the question, please?
Q. Does the disclosure of the '627 patent ever talk about dimensionality of a signal point?
A. It says a "2N-dimensional signaling scheme."
I mean -- and in the -- you know, in the summary of the invention it has been realized that the Viterbi decoder performance in a data communication system using 2N-dimensional channel symbols.
Q. Okay. So it talks about 2N-dimensional signaling scheme. And you equate that as requiring a two-dimensional signaling point?
MR. TROPP: Can I hear that last question back.

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(Requested portion of record read.)
A. If I look at all of the figures, they all refer to QAM systems.
Q. By "all of the figures" --
A. Figure 3 -- they all have QAM.
So figure 3 is a block diagram of the transmitter section of the modem applying four-dimensional channel symbols and embodying the principles of the invention, and it has QAM encoded.
So, you know, I interpret it as the 2N-dimensional channel symbols where the constituent points are QAM, and N refers to the number of such points that comprise a channel symbol.
Q. Let's look at claim 1.
Does claim 1 specify the dimensionality of a signal point?
MR. TROPP: Objection.
(The witness reads document.)
A. So it's -- it implies -- it says: "Means for generating a plurality of streams of trellis encoded channel systems."
Q. How does that --

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A. Can I read on?
"Each of said channel systems being comprised by a plurality of signal points."
So that says to me that this is a multi-dimensional system, and a symbol is comprised of more than one signal point.
Q. That's correct.
The channel -- the claim 1 requires that the channel symbols are multi-dimensional, which means they are composed of more than one signal point; is that right?
A. The --
(The witness reads document.)
A. It says that the channel symbols are comprised of a plurality of signal points.
So I interpret the 2N to mean that the basic signaling is QAM. And when you say 2N, it's the channel symbol is comprised of N two-dimensional signal points.
Q. Where in claim 1 do you see the words "2N"?
A. Well, I mean, the context of the whole patent, it starts out in the abstract. Using 2N-dimensional channel symbols, N greater than 1.

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Okay?
And when -- so if you -- let's see...
And in the -- in the summary of the invention it says: "A data communication system using a 2N-dimensional channel symbol.
Line 14: "In preferred embodiments of the invention, the interleaver is carried out in such a way that every N signal point of a respective -- of respective channel symbols."
That implies to me that the constituent point has two dimensions. It's a 2N-dimensional symbol. And if it has N signal points, each of the signal points, by inference, then, is two-dimensional.
Q. So we agree that the specification of the patent implies that signal points are two-dimensional? That's what you just stated?
A. I would say that the specification says that.
Q. My question is: Does claim 1 require it?
MR. TROPP: Objection.
Q. Let me rephrase that.
Does claim 1 require that the signaling

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scheme to be used is 2N-dimensional?
MR. TROPP: Objection.
A. Well, the claim says that the channel symbols are comprised of a plurality of signal points, and the spec teaches that each signal point is two-dimensional.
Q. Okay. When the claim states "channel symbols are comprised of a plurality of signal points," doesn't that mean that the signaling scheme that the claim requires is N-dimensional?
MR. TROPP: Objection.
A. The whole patent deals with 2N-dimensional. In the abstract it says 2N-dimensional channel symbols. In the summary of the invention is 2N-dimensional channel symbols.
If they wanted to do what you said, they would say N-dimensional channel symbols. They wouldn't have the constant "2" in there.
Q. The constant "2" does come into play in dependent claim 3; do you see that?
(The witness reads document.)
Q. Do you agree -- were you going to confirm that, or should I continue my question?
A. I didn't hear a question.

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MR. TROPP: I think the question that was on the table was whether you see that claim 3 brings the term "2N" into the claim language.
A. I'm reading claim 3.
(The witness reads document.)
A. Yes.
Q. Would you agree that claim 3 is a further limitation of claim 1?
A. My -- my understanding of this is that I read claim 1 in the context of the specification. And so that claim 3 seems to be just a further clarification, but not a restriction.
I understood the words of claim -- of claim 3 to be what the invention is about.
Q. Okay. So your understanding is that claim 1 is already limited to two-dimensional signal points and claim 3 is a further clarification, of that requirement?
A. Yeah. Based upon the spec.
When I read, you know, claim 1, that spec, from the arguments I went through about 2N-dimensional word phrasing in the summary of the invention, the abstract, and a detailed description, I interpreted it that way.

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Q. Have you heard of the doctrine of claim differentiation?
A. I've heard it, but I'm not an attorney, so...
Q. What it says is that dependent claims -- strike that.
What it says is that all claims have meaning, and they're not simply clarifications, as you've stated.
Claim 3 must be a further limitation of claim 1 for it to be allowed.
MR. TROPP: I haven't heard a question yet.
Q. Therefore, wouldn't you agree that claim 3 must be a further limitation of claim 1?
MR. TROPP: I object to the question and to the legal characterizations therein.
A. I'm not an attorney, so I'm not -- I can't comment on what you said.
Q. Wouldn't you agree that claim 3 would be meaningless if claim 1 were interpreted the way you proposed?
MR. TROPP: Objection.
A. I'm not going to comment on the quality

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of the patent.
Q. Okay.
Can we go to column 8, lines 58 through 61.
Can you read that statement from lines 58 to 61?
(The witness reads document.)
A. I read on through line 64.
Q. Can you read that sentence into the record?
A. Which sentence?
Q. Starting with "Thus."
A. "Thus, although the illustrative embodiment utilizes a four-dimensional signal in this scheme, the invention can be used with signaling schemes of any dimensionality. In general, 2N-dimensional case, each stage of the distributed trellis encoder would provide N two-dimensional subset identifiers to switching circuit 337, before the latter moves on to the next stage."
Q. But the sentence between lines 58 through 61, do you ascribe any meaning to this sentence?

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A. It's -- you're taking something out of context. I prefer -- I read what I -- I kept reading, and the next sentence to me describes the essence of it, of the invention. Or -- or 2N-dimensional system. N two-dimensional subset identifiers, which is consistent with what I said. Each constituent point is two-dimensional. You provide --

Q. So we can agree that the preferred embodiment of the '627 describes a 2N-dimensional case?

MR. TROPP: Objection.

A. No. It says in the general case.

Q. What is the preferred embodiment of this invention? Which signal dimensionality does it use?

A. It says...

(The witness reviews document.)

A. All the figures relate to four-dimensional channel symbols.

Q. Which is -- four dimensional channel symbol is -- could also be called a 2N-dimensional channel symbol?

A. You asked me about the preferred

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embodiment. All the figures deal with four-dimensional channel symbols.

Q. Could the invention be used with an eight-dimensional channel symbols?

A. Yes.

Q. Could the invention be used with six-dimensional channel symbols?

A. That would be over three signal points -- three two-dimensional signal points.

Q. Can the invention be used with a one-dimensional signaling point?

A. It's -- it's 2N, and -- depending upon where you look, N is greater than 1. That's not the context of the invention.

Q. My question is whether the invention can be used with one-dimensional signaling -- signal points.

(The witness reviews document.)

A. The invention deals with 2N-dimensional channel symbols.

Q. I understand that the -- that the '627 specification refers to 2N-dimensional channel symbols.

However, in your opinion, would this

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invention (indicating) of the '627 patent still work for a one-dimensional --

MR. TROPP: Objection.

Q. -- case?

A. I would have to think about that. I'm not --

Q. So sitting here today, you don't have an opinion as to whether--

A. I don't have an opinion.

MR. TROPP: Is now a convenient time to break for lunch?

MR. KOLMYKOV: Sure.

THE VIDEO OPERATOR: The time is 12:59 p.m., and we're going off the record.

(Time noted: 12:59 p.m.)

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A F T E R N O O N S E S S I O N:

(Time noted: 1:43 p.m.)

THE VIDEO OPERATOR: The time is 1:43 p.m., and we're back on the record.

R I C H A R D D. G I T L I N,

resumed, having been previously duly sworn, was examined and testified further as follows:

CONTINUED EXAMINATION

BY MR. KOLMYKOV:

Q. Did you have a nice lunch?

A. Yes. How about you?

Q. Good. Good.

We ended up with discussing the sentence of the '627 patent in the column 8 which reads: "Thus, although the illustrative embodiment utilizes a four-dimensional signaling scheme, the invention can be used with signaling schemes of any dimensionality."

By -- when the specification refers to the words "any dimensionality," could it possibly include a one-dimensional signal point?

A. Not from my reading. I mean, it -- if you look at the construction of 2N in the abstract, it says 2N is greater than 1.

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So we're dealing with four-dimensional unchanneled symbols.

Everywhere the inventors use 2N it's clear to me that -- and then in figure 1 they say "employs a 2N-dimensional signaling scheme, N greater than or equal to 1."

So the constituent underlying signal constellation, the signal points are two-dimensional.

So -- I mean, I think the scope of the patent -- that's the scope of the patent.

Q. But this sentence in particular, could it also refer to a one-dimensional signal point?

A. Which line are we on again?

Q. When it says "signaling schemes of any dimensionality."

(The witness reads document.)

MR. TROPP: Object to the form of the question.

A. I think the sentence -- I can't -- I'm not going to take one sentence that you isolate out of context and make sense -- "In the general 2N dimensional case, each stage of the distributed trellis encoder will provide N2-dimensional subset

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identifiers."

So that's the construct -- the context of the patent.

Q. Would a burst error affect the one-dimensional signal as well?

A. Sure.

Q. Would a signal point interleaving technique, without considering the '627 patent, possibly be used with one-dimensional signal points?

MR. TROPP: Objection.

A. I mean, the word -- so the word "signal point" in my mind, I'm thinking -- always thinking of it as a two-dimensional signal point.

Q. Let's think of one-dimensional points.

Can you interleave one --

A. Gallager, as one example in his book, he calls it interlacing of quantities, which are just numbers.

That would be an example of interleaving one-dimensional -- scalers.

Q. Let's look at Gallager for a second. I believe it's on page --

A. The book or the patent?

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Q. The reference, the Gallager reference, starts on page D 0092 of your declaration. Figure 610-1 on page 95 illustrates interleaving of simply data units.

Is that correct?

A. It illustrates as Gallager says. The incoming stream of binary data is separated to a fixed number, say R, of data streams, as shown in figure 6.10.1 of Gallager's book.

Q. These data streams are not streams of signal points; they're streams of channel symbols.

Is that correct?

A. The streams -- no. They are streams of binary data.

Q. Okay.

So the Gallager reference just interlaces or, in other words, interleaves binary data?

A. Yes.

Q. Is it possible to design a trellis encoder to generate multi-dimensional trellis-encoded channel symbols where each is one-dimensional?

A. I haven't thought much about it, but I

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think that's possible.

Q. Is it possible to concatenate two one-dimensional signal points and create a two-dimensional channel symbol?

A. The -- the basic principle of trellis encoding is that you have a state transition, and that's based upon input, the current state of the encoder, and that produces an expanded bit set.

And so that -- when -- excuse me -- when you talk about trellis coding, that's the elemental, the basic notion that one state transition produces one expanded bit set that, then, there's a series of operations to produce the trellis-coded symbol.

Q. Okay. But that wasn't my question.

My question was whether it is possible to concatenate two one-dimensional symbol points and create a two-dimensional channel symbol.

MR. TROPP: Objection.

A. I don't think that's the question you asked me. You had trellis coding in the first time you asked it. I thought that's what I heard.

If you could repeat the question now, I'll try and answer it.

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Q. Is it possible to design a trellis encoder that concatenates two one-dimensional signal points and creates a two-dimensional channel symbol?

A. The -- if you're signaling alphabet -- this is unrelated to the Betts patent.

Q. Okay.

A. If your underlying signaling technique is one-dimensional, say amplitude modulation --

Q. Yes.

A. -- then if you have a multi-dimensional trellis encoder, it will produce at the output subset identifiers. And in your case you want to produce two of them. And each one of them, with the aid of the uncoded bits, will specify a signal point in interval 1 and a signal point in interval 2.

That's the way I would say you could -- that's the way I interpreted your question and that's a system that would do that.

Q. And that would produce a two-dimensional channel symbol? Because there are two signal points --

A. It's a two-dimensional encoded --

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trellis-coded symbol.

Q. Okay.

Does a trellis encoder require a modulation encoder?

MR. TROPP: I'm sorry, can I hear that back.

THE WITNESS: Can you repeat the question?

Q. Does a trellis encoder require a modulation encoder?

A. By "modulation encoder," could you be more specific?

Q. Such as a unit that out of its input creates signal points out of the inputted bits, it creates signal points that would be a modulation encoder.

A. What are you referring to as "it"?

Q. Let me rephrase that question.

Trellis encoding consists of two different techniques, as you mentioned earlier: Modulation and coding.

Is that correct?

A. The -- trellis coding, the significance of trellis coding was that it combines coding and

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modulation. But the modulation is -- has two steps involved. People often confuse this.

A modulation in the trellis coding sense, at the output of the bit expander you have discrete bits. That, then, has to map into a signal point.

You have a signal point, which is a pair of numbers.

Then, if we're using QAM transmission, then -- if this was a two-dimensional trellis code and output, you modulate the sine and cosine.

So there are two levels of modulation. You go from the output of a bid expansion to a signal point, which is a pair of numbers, X and Y coordinate -- in-phase and quadrature.

Then you apply them to the sine and cosine. Then of course put them through a band-shaping filter.

So modulation is two steps.

Q. So the first step of the modulation, as I understand, is the mapping of the bits to create a signal point.

That's what you just said; is that right?

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A. Yes.

Q. When I speak of a "trellis encoder," does it require to have in it the circuit that performs this bit mapping?

A. The mapping of the bits --

Q. Into a signal point.

A. I think this is a question of opinion.

I think to me that is an important part of a trellis encoder.

Q. But can a trellis encoder be incorporated in one device, one circuit, that does the encoding of the bits as well as the bit mapping into a signal point?

A. When you say "one circuit," what do you mean?

Q. I mean one chip.

A. Well, from my experience, in the voice band modem range these would be lines of DSP code and you would execute this on a DSP. So you would do many of the operations on the DSP.

"DSP" meaning digital signal processor.

Q. And these digital signal processors, they process certain code; is that correct?

A. They have software that's written that

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manipulates the signals -- they are already in digital form.
Q. So trellis encoding and the bit mapping into signal points can all be implemented in software?
A. I wouldn't -- you drew a distinction which I don't accept. Trellis encoding includes the mapping into the signal points.
Q. And this bit mapping together with the encoding or expansion of the input bits can be performed in software?
A. It depends on the rates in which you're processing. So if you're processing at a rate where the chip or the ASIC can do it, you can do this all in one device.
But if you were operating at a very, very high bit rate, it might not be possible to do this in one device.
Q. Can you give me an example of a bit rate that a single device cannot handle?
A. Well, I can make up a very large number.
Suppose I wanted to build 100 gigabit system.
MR. TROPP: Just out of curiosity, we're

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still on his declaration in some form?
MR. KOLMYKOV: Yeah.
MR. TROPP: Yeah? I'm having trouble understanding the connection. But on your representation that's where we are, go ahead.
MR. KOLMYKOV: I'm continuing with his description of trellis encoding and what it means.
MR. TROPP: I'm not sure you're continuing with his description. But on your representation that that's where you are, go ahead.
BY MR. KOLMYKOV:
Q. Well, let's refer to figure 3 of the '627 patent.
A. Just a minute.
Q. Do you see a QAM encoder designated as 324?
A. Yes. Yes.
Q. And you see the 4D trellis encoders: 319 alpha, 319 beta, 319 gamma?
A. I see what he labels as trellis encoders.
Q. So my question to you is whether the unit 324 and the units 319 alpha, beta and gamma can be implemented together in one device?

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A. As I said, it depends upon the speed of application. You -- one of the tenets of communication systems to get cost-conscious designs is to combine elements.
So in principle, almost all, especially digital elements, could be combined. Assuming the processor has enough speed.
Q. All right, thank you.
During your discussion of the trellis encoding you mentioned that a trellis encoded channel symbol is generated to one expansion of the input bits; is that correct?
A. Yes.
Q. Is it fair to say that a channel symbol is a group of bits?
A. A channel -- in the context of the panel, or --
Q. In general.
A. It's -- you know, it's a word that's used in multiple contexts. So without saying specifically what are you talking about, it could have several meanings.
My declaration interprets it in the context of the patent.

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Q. Okay. Let's start with outside the contents of the patent.
In your opinion, as a person of ordinary skill in the art, is a channel symbol a group of bits?
MR. TROPP: Objection.
A. It could have many meanings. I think you have to get more specific.
Q. What does a channel symbol represent? Does it represent the bits?
A. It has -- yeah, I prefer not to speculate. I prefer to talk about the meaning in the context of the specific system.
Q. In your opinion, who is the ordinary -- who's the person skilled in the art, the ordinary person skilled in the art?
A. In the context of this patent?
Q. In the context of this patent.
A. Someone who has probably a master's degree in electrical engineering, maybe computer science, and a reasonable amount of experience, three to five years, maybe.
Q. So you would consider yourself such a person?

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MR. TROPP: Objection.
A. I have a lot of experience in this.
Q. So, in other words, you would consider yourself an ordinary person skilled in the art?
MR. TROPP: Objection.
A. Okay.
Q. Is that a yes or a no?
A. Yes.
Q. So in the context of the '627 patent, what is a channel symbol? Is it fair to say that it's a group of bits?
A. What's referred to is a trellis-encoded channel symbol.
So that's an output of a trellis encoder. And depending upon the dimensionality, it will be mapped into signal points that are transmitted over one or more intervals. Two-dimensional signal points that are transmitted over one or more signaling intervals.
Q. But once the channel symbol is transmitted, what does the receiver receive? A group of bits?
A. The receiver receives analog wave form.
Q. Okay. Let's start at the transmitter.

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When the channel symbol -- the trellis-encoded channel symbol is generated by a combination of the plurality of the trellis encoders and the QAM encoder, the result is a group of bits?
MR. TROPP: Objection.
A. Are you referring to figure 3?
Q. Yes, I am referring to figure 3.
A. And what result are you talking about?
Q. I'm talking about the result on line 325.
A. That generates a -- depending upon the dimensionality, it generates a sequence of two-dimensional signal points, and they have been interleaved. And the signal points coming from, let's say trellis encoder alpha, if it's four-dimensional then each time you get an input in the bit expansion it generates two two-dimensional signal points.
Q. So you agree that line 325 carries interleaved signal points?
MR. TROPP: Objection.
A. The 325 -- I mean, the patent -- the element that produces 325 is 4D QAM encoder. So I

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can only -- it doesn't give me enough detail to say the precise format of what the signals at 325 are.
Q. Okay.
But the signals on line 325, if you were able to see them, they would just look like zeros and 1s?
A. No. They would look like two -- there would be pairs of numbers taken from -- in this case, they would be grouped. The two-dimensional constituent points, you would have a sequence of two-dimensional numbers. Related to the alphabet for the constituent two-dimensional signal constellation.
Q. And one point out of that constellation is called a signal point?
A. Yes.
Q. And a signal point could be represented as zeros and 1s?
A. No. A signal point is chosen from an alphabet.
So, for example, if you look at figure 2 from the patent, the signal point there is -- I assume, if you look at figure 2, that the axes must be plus or minus 1, plus or minus 3 or 5 in the X

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and Y, and then there's the obvious association; let's say C6 would be plus 5, comma 3 volts.
Q. How does the processor, a DSP, receive these groups of channel symbols?
A. I think your question was unclear.
Q. What form do these groups of channel symbols take on line 325?
A. You mean what's the arithmetic --
MR. TROPP: Objection.
A. -- that the DSP uses?
THE WITNESS: Sorry.
Q. Doesn't the processor operate on data -- on digital data?
A. Yeah. That's called -- DSP operates on digital data.
Q. So, therefore, what the processor sees are bits?
A. It has a numbers representation. It could be deuce complements, sine magnitude.
That's not -- in terms of the modulation, what's important is the analog level that is represented by this numbers representation.
The fact that it's bits is just for the convenience of a DSP. If you did it some other

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way, you don't have to use a DSP.

The point is you're going to I and Q modulate the sine and cosine in element 328.

Q. But in practice a DSP operates on bits?

A. Yeah, but that's not -- that's immaterial to the invention of the patent. That doesn't matter.

Q. I am just asking a general question.

A. DSP operates on digital representations of real numbers.

Q. How does a physical digital signal processor can operate on a representation of numbers?

A. It converts them to some arithmetic. For example -- I gave you two examples: Deuce complements or sine magnitude which are strings of binary digits.

But that's just incidental. That has nothing to do with the core information bits that are being transmitted. That's just a means of representing them for the convenience of a digital signal processor.

Q. Right. So mathematically they are represented in constellations and complex numbers,

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for example, but the actual device operates on actual bits, not on some X and Y coordinates?

MR. TROPP: Objection.

THE WITNESS: I'm sorry.

A. It operates on X and Y coordinates. It manipulates them in terms of a number representation. They are a bit stream. But that's immaterial to what's going on here.

Q. Let's look at your figure in your declaration, the figure on page 5.

What are X2 and X1?

A. What are they?

Q. Yeah. What are they?

A. They are the inputs to the trellis encoder.

Q. What form are they in?

A. Binary.

Q. So they are bits?

A. They are bits.

Q. And this figure shows a trellis-coded modulator?

A. This is taken from one of Ungerboek's articles.

Q. So the encoder operates on bits X2 and

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X1?

A. Yes. That's the input.

Q. What are Y2, Y1, Y0?

A. That's the output of the -- that's the result of one-bit expansion or state transition. So you've now expanded from two bits input to three bits output.

Q. And it calculates these output bits -- Y2, Y1, Y0 -- based on the inputs bits X2 and X1; is that correct?

A. And the current state of the shift registers.

Q. But the current state of the shift register depends on what X1 is?

A. It depends on the previous value. These are delay elements. These depend on the history of the inputs and the current input.

Q. So is it fair to say that the expansion of a redundant bit depends on the input bit as well as the state of a convolution encoder?

A. Can you ask the question again?

Q. Is it correct to say that the expansion of a redundant bit depends on the input bits as well as the state of the convolutional encoder?

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A. What do you mean by the "expansion bit"?

Q. By the "expansion bit" I mean Y0.

A. Well, YO depends upon the current input and the state of the shift register device.

Q. Okay.

To sum up, the output Y2, Y1, Y0 -- in other words, the expanded bit group -- depends on the input as well as the state of a convolutional encoder?

A. Yes.

Q. And these output bits are calculated based on the sequence of the input bits?

A. I mean, the input is presented the shift register cycles and you produce the output, three-tuple bits.

Q. The output bits are dependent on the input bits and what the sequence of these input bits really is?

A. Yes.

Q. Can the trellis encoder operate under one group of input bits at a time?

A. I'm not -- I don't understand the question.

Q. Well, let me rephrase that question.

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Are the three bits in your example output in one signaling interval?

A. In this example (indicating).

Q. So --

A. I want to finish.

Q. Yeah.

A. The way it works in this example, you output -- you get an input, the shift register cycles. You compute the output, Y0, Y1, Y2. You have the bit to symbol mapping, which is the form of modulation I referred to before. And then it tells you which of the eight signal points are going to the modulator. So this is a two-dimensional trellis code.

Q. So in one signaling interval it generates three output bits?

A. It -- it generates three bits that, then, are -- go to the table, and there's a one-to-one correspondence between those three output bits. And the two -- the two-dimensional signal point, P0 through P7, one of those eight is selected.

Q. Okay. So this whole process in your examples occurs in one signal interval?

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A. Yes.

Q. To generate one signal point?

A. In this example. This is a, you know, a two-dimensional trellis encoder.

Q. Okay. In this example, you operate on two bits in one signaling interval?

A. You process two inputs, produce three output bits of the a convolutional encoder. You map that through the bit of the symbol mapper and then you produce a signal point, a two-dimensional signal point. That's what you do.

Q. Does one group of input bits lead to one trellis-encoded channel symbol?

A. In general, or in this example in paragraph 11?

Q. Let's start with this example.

A. So that's what this shows. Each pair of inputs X1 and X2 at the end of the chain produce a signal point.

Q. Could there be a relationship between the input bits of the trellis encoder?

A. Do you mean X1 and X2?

Q. Yes.

A. Could there be a relationship?

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Q. Yes. Could there be a relationship?

A. In general --

Q. In general.

A. In general they are not. They are just streams of however you parse your input bit stream in X1 and X2.

Q. Let's refer to page 16 of your declaration, paragraph 31. About half of the way down --

A. Could I read paragraph 31?

Q. Sure.

(The witness reads document.)

MR. KOLMYKOV: Let's change the tape while he's reading.

THE VIDEO OPERATOR: This ends Tape Number 2, the time is 2:24 p.m., and we're going off the record.

(A recess was taken.)

THE VIDEO OPERATOR: This is Tape Number 3. The time is 2:31 p.m., and we're back on the record.

BY MR. KOLMYKOV:

Q. Did you get a chance to read paragraph 31?

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A. Yes.

Q. So the sentence that starts with "The '627 patent would be pointless," can you read that sentence?

(The witness reads document.)

A. I read it.

Q. You state that: "The '627 patent would be pointless or at least undifferentiated from the '625 patent if there were no inherent relationship between the signal points of a given trellis-encoded channel symbol."

And you continue: "Beyond that which is always present among the stream of signal points processed by the same encoder."

What if there was an inherent relationship between the signal points; would your statement not apply?

MR. TROPP: Objection.

A. The context of the patent, '627 patent, for example, deals with multi-dimensional trellis-encoded symbols.

So let's take an example.

Four-dimensional.

So the one state transition, the bit

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expansion produces a -- after you go through the bit to symbol mapping to 2D signal points. Two times 2D is the 4D. And those are produced by the same encoder.

So now they are related.

Q. What about the case where there are two one-dimensional signal points transmitted instead of one two-dimensional signal point?

A. What system are you talking about?

Q. I'm talking about, in general, a one-dimensional modulation system?

MR. TROPP: Is there a question?

MR. KOLMYKOV: Yes, there was a pending question.

MR. TROPP: Object to the form of the question. I don't understand the question.

A. Could you repeat the question?

Q. What about the case where there are two one-dimensional signal points transmitted instead of one two-dimensional signal point: What relationship is there between the two one-dimensional signal points?

A. Are we talking about a multi-dimensional trellis encoder?

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Q. Yes.

A. So, for example, if each of the constituent points were one-dimensional and you had a four-dimensional system, you would produce, from one-state transition, four one-dimensional outputs, and they would be related. Because they were produced by the same trellis encoder.

Q. So if you produced four outputs, those four outputs are produced in four expansions?

A. One expansion. I said a four-dimensional trellis-coding system.

Q. Can you envision an input where the bits on the input are interrelated?

A. Interrelated in what sense?

Q. For example, let's take a Reed Solomon -- R-e-e-d, S-o-l-o-m-o-n -- encoder. What type of output does it generate?

A. Does what generate?

Q. A Reed Solomon encoder.

A. It generates -- you know, at this moment I don't recall all the details, so I'm not going to talk about the Reed Solomon coder.

Q. So you're not familiar with the Reed Solomon encoder?

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A. I am. But right now it's not on the top of my conscious. I've been exposed to Reed Solomon codes.

Q. What is your understanding of a Reed Solomon encoder?

MR. TROPP: He's told you that he's uncomfortable with this line of questioning and it's beyond the scope of his declaration, so I'm wondering why you're pursuing it.

Q. Isn't it true that a Reed Solomon encoder generates a block of data, a block of bits, where bits are interrelated?

MR. TROPP: Hang on a second. Are we not going to have the discussion I'm trying to have?

MR. KOLMYKOV: I don't see what the point is of having this discussion. I'm asking a question --

MR. TROPP: The point is that we agreed that this deposition was going to be focused on --

MR. KOLMYKOV: Are you instructing him not to answer?

MR. TROPP: -- the scope of the declaration, with limited additional subjects in

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the margins.

And it seems to me we may be reaching a place where you're going beyond the agreed-upon bounds of the deposition.

I prefer not to have to instruct him not to answer, but I was looking for an answer to my question so I would know where we are and where we are going.

MR. KOLMYKOV: This is where we are going. I'm trying to establish whether Professor Gitlin is aware of a situation where there is an inherent relationship among the inputted bits. Whether there is a case where the input into a trellis encoder is already formed in such a way where the input bits are interrelated.

MR. TROPP: Okay. Without arguing with you and without trying to challenge your premise, how much more time do you plan to spend on Reed Solomon encoders, which go beyond the scope of his declaration?

MR. KOLMYKOV: I would just like him to think of other types of inputs. Can he envision those inputs. I'm not going to ask him about Reed Solomon.

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BY MR. KOLMYKOV:

Q. But would that be one example?

MR. TROPP: Let's see where it goes. I do hope that you will confine yourself to the declaration. And I'm not sure at the moment whether you're going beyond or not. So I'm going to take it a question at a time.

A. I could imagine a case where the original source input, let's say, for example, was speech, and you sampled it, and the samples have a correlation, because it's not white noise, it's speech.

And thus, the input bits going into the trellis encoder might have, under those circumstances, have some correlation.

Q. So, then, this correlation among input bits would carry through the trellis encoder where the signal points produced are also interrelated because of this initial correlation?

A. Well, the -- the whole purpose of a trellis encoder is, when you look at a trellis diagram or a state diagram, is to produce a sequence of channel-encoded symbols, and therefore represented by signal points that are correlated

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and have a relationship independently of whether the input was dependent or not.

Q. Okay.

But the initial correlation of the input would carry through the trellis encoder and create another interdependency?

A. I would -- I haven't analyzed that. And, you know, it's possible that the actual processing of the trellis encoder may -- may have an effect where it increases the dependency or it doesn't. I haven't considered that case.

Q. You haven't considered the alternative of your statement in paragraph 31, where you state, "If there were no inherent relationship"?

A. What I was referring to there was the relationship between the signal points produced by a multi-dimensional trellis encoder. Meaning that independently the input, the signals that come out, let's say produced by a 4D trellis encoder with constituent 2D points, those two signal points will be -- have an inherent relationship independently of what the input was. Because they were produced by the trellis coder as a result of a single bit expansion or state transition.

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That's what I meant.

Q. Okay. You spoke earlier about expansion of input bits. Could you clarify for me, what does the trellis encoder precisely expand?

A. So if I could refer you to paragraph 11 of my declaration on page 5, this is a two-dimensional system and you have two bits going into the box and you have three bits going out. So you've expanded a number of bits from two to three, or you might say it's a rate two-thirds code; two being the input, three being the output.

Q. So does one expansion always correlate to adding one bit?

A. In multi-dimensional systems -- there are various systems that are much more complicated than this that may go beyond that. But typically for efficiency reasons the codes are N over N plus 1. That is, adds one bit.

Q. Okay, but there are cases where the code rate could be something other than N over N plus 1?

A. It could be. I'm giving over here the standard case.

Q. Okay.

Can a trellis encoder be designed to

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perform expansions in different ways?

For example, in paragraph 12 you illustrate that two bits are expanded into three all at once. Is that correct?

A. Two bits are presented to the machine. The machine goes through a cycle and it produces three output bits.

Q. So two bits are expanded into three in one cycle?

A. Yes.

Q. Is it possible to design a trellis encoder to expand four bits in one cycle?

A. You mean have four bits as the input?

Q. Yes.

A. That's certainly possible.

Q. Is it possible to design a trellis encoder to expand eight bits in one cycle?

A. Yes.

Q. Is it possible to encode four bits and produce an output of eight bits; is it possible?

A. I'm not sure --

Q. Could you encode four input bits into eight output bits using a trellis?

A. Using...?

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Q. A trellis encoder.
A. I could conceive of an arrangement where you could have a multiple -- a convolutional code that has more complexity. I guess it's possible. Although I haven't thought about it. It wouldn't make much sense because it would be an extremely inefficient system, so there would be no purpose for doing that.
Q. But it is conceivable to design a system to design four bits into eight output bits in one cycle?
A. I guess you would need a convolutional -- it would be a much more complicated system. They would have a more difficult state description. But I'm not familiar with such systems. I've never seen anyone do it and I see no practical reason why you would do it.
Q. But theoretically it is possible?
A. Maybe I won't care to speculate.
Q. Can we design a trellis -- strike that.
Can a trellis encoder be designed to encode a group of four bits to produce eight output bits in four expansions?
A. Trellis encoder deals with one

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expansion. So it's not -- the way trellis encoders -- you can invent a new type of encoder. But a trellis encoder deals with what happens when I have a state transition. That's the element -- the basic element of a trellis encoder. It deals with one state transition.
Q. Are you assuming that one expansion is always the addition of one bit in a trellis encoder?
A. Inputs are presented to the -- for example, the figure I have on page 6, you can put any complexity you want. Inputs are presented, outputs are produced. That's one state transition of the encoder. And that's the way trellis encoders are defined.
Q. And you state it that you could have a trellis encoder that has an input of N bits and produces an output of either N plus 1 or N plus 2 or N plus 3 and so on bits?
MR. TROPP: Objection.
A. In one state transition?
Q. In one state transition.
A. The most common is to produce one more. And I could not see any reason, for efficient

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communications, to do more than that.
Q. Are you aware that the Wei reference does allow for the case for trellis encoders of rates other than N over N plus 1?
MR. TROPP: Which reference?
A. Which reference?
Q. Let's look at page D 0052.
A. Which exhibit is it?
Q. Of your declaration.
MR. TROPP: The penultimate page of Exhibit C.
Q. The very last paragraph of the article.
(The witness reads document.)
A. I've read this paper before, and -- and I refer to it in my declaration for a demonstration of prior art on four-dimensional systems. But I didn't review it in great detail to deal with comments on -- I didn't study this paper in great detail to comment on trellis codes -- how he does it, rather than N over N plus 1.
Q. But can you read the last paragraph on page 52?
(The witness reads document.)
A. Yes. He says that the trellis codes of

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rate other than M over M plus 1.
Q. So he does leave a possibility of using other trellis codes?
A. That's what he says. I haven't studied this paper in that level of detail to comment on that.
Q. So it is possible to design a trellis encoder that can generate eight output bits from four input bits in any number of expansions?
MR. TROPP: Objection.
A. To me a trellis coder deals with a single expansion.
Q. But it is possible to design an encoder that can perform many expansions to generate a certain output in one cycle?
MR. TROPP: Objection.
A. Yeah -- that seems inconsistent. Yeah, I think -- many expansions in one cycle. One cycle refers to a single expansion. So I don't agree with the hypothesis that you have.
Q. Can a trellis encoder encode -- we've already established that a trellis encoder could encode two bits in one cycle; is that correct?
A. Accept an input of two bits?

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Q. Yes, in one cycle, as well as accept four bits and encode those four bits in one cycle?

A. It can accept an arbitrary number of bits at the input.

Q. And you understand that when I refer to a "cycle" I refer to a signaling interval?

A. I refer -- cycle is one cycle through the state machine.

Q. What is "one cycle through a state machine"?

A. It's an interval of time. For example, in a four-dimensional system you would produce two two-dimensional points and they would be output over two signaling intervals.

So the machine is processing -- it has a different time reference. The signals as they are going out in the line, every capital T seconds let's say is a signaling interval, you are producing a two-dimensional point.

But the 4D trellis coder, every time it goes through a state transition, produces two of these 2-D points.

Signaling interval only has relevance when you're modulating the signal and going out on

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the line. It doesn't have necessarily relevance to the way the state machine is working.

Q. When you're talking about generating signal points on a line, what are you referring to?

A. Producing the signal points -- a sequence -- let's see. Coming back to my example, a four-dimensional trellis coded symbol. Every time it goes through a state change, it produces two two-dimensional points.

Each of these points, amplitude -- or modulate respective of the in-phasing quadrature signal, in that case over two signaling intervals.

Q. And to produce those two signal points the encoder, in your opinion, performs one expansion?

A. Absolutely. That's the whole idea of a multi-dimensional trellis coding.

Q. Can you generate four signal points in one expansion?

A. If you were building an eight-dimensional trellis coder where the constituent points are two-dimensional, you would generate -- so you would have an eight-dimensional system, you would build -- it would produce four

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subset identifiers, and that would then, in the context with the other uncoded bits, produce four two-dimensional signal points. You would thus be constructing an eight-dimensional system.

Q. So let's say we have an input of eight bits and you want to generate four signal points, you want to generate 12 bits, so you have an input of eight bits, and you want to generate 12 bits.

How many expansions does that require?

MR. TROPP: Objection.

A. To me a trellis encoder you either -- is defined around one expansion.

Q. But it is possible to implement a trellis encoder that could generate 12 bits out of eight bits in one expansion?

MR. TROPP: Objection.

A. That's -- you know, I haven't thought much about it. Wei said that in the last paragraph of his paper.

Q. So do you have an opinion as to whether he could generate 12 bits out of eight bits in one expansion?

A. In one cycle through the machine and one expansion, it seems possible.

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Q. So the number of expansions is dependent on the type of trellis encoder that you are implementing?

A. The number of expansions or the degree of expansion?

Q. The number of expansions.

A. That's not what I said. There's only one expansion. You go from M inputs to N outputs. And I'm thinking it's N over N plus 1. It's all from a single expansion, a single state transition.

Q. Are you familiar with the concept of expanding bits in a trellis encoder using matrix multiplication?

A. No.

MR. KOLMYKOV: Let's mark Defendants' brief as the next exhibit.

(Gitlin Exhibit 3 marked for identification, Defendants' opening claim construction brief concerning the U.S. Patent 5,243,627.)

BY MR. KOLMYKOV:

Q. Let's refer to page 10 --

A. I have never seen -- I don't believe I've seen this document.

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Q. So you've never seen Exhibit 3, which is Defendants' opening claim construction brief concerning the U.S. Patent 5,243,627?
A. This is dated June 4, 2008. I don't believe I've seen this.
Q. Okay. Can you just read, on page 10 -- can you go to page 10.
(The witness complies.)
Q. And I would like you to read the first sentence of the second full paragraph.
(The witness reads document.)
Q. Can you read that into the record?
A. I mean, I'm reluctant to read something out of context. Can I read the whole section 3? This is a complicated document.
MR. JUISTER: That's one page.
THE WITNESS: Sorry.
MR. JUISTER: Yeah. If you need to read the document, read the document.
A. I have never seen this before.
MR. TROPP: It's a fair request. He asked you to read the sentence --
A. I would actually like to look at the document. I mean, I've never seen it before.

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Q. Sure. You can skim through the document.
A. I'm going to read through the document. I haven't seen it before.
Q. Let's instead go back to your declaration, then. Page 12. The bottom right, above where paragraph 24 starts. The last sentence of the preceding paragraph, starting with: "As a result, only one extra bit is added for every two signal points, instead of one for every signal point, as in a two-dimensional TCM."
What is the difference between a multi-dimensional TCM and a two-dimensional TCM? Let's start with that.
A. In a two-dimensional TCM, the "two" refers to that the two points are a QAM signal point, which is two-dimensional. And each state transition or signal expansion when you go through the whole system produces one signal point.
In a 2N-dimensional system, again, the constituent points are two-dimensional, and an N dimensional system produces N output -- N signal points.
Q. In your opinion, the only way to

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generate channel symbols comprising multiple signal points is through one expansion of input data?
MR. TROPP: Objection.
Q. Is that correct?
A. I didn't say that.
In my opinion, multi-dimensional trellis coders are understood to operate the way I described.
Q. And you described the trellis encoders as always operating in one cycle and in one expansion of input data?
A. That's -- that's the way trellis encoders work. That's the way they've been deployed and that's what I said.
So you have input, you have a state transition, it produces expanded bits, in a -- for example, coming back to the four-dimensional case, it produces at the output two two-dimensional signal points.
Q. Okay.
In your declaration you talk about the advantage of adding one extra bit for every two signal points, as opposed to one bit for every signal point.

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What is that advantage?
A. What is the consequence of doing that?
Q. What is the consequence of doing -- adding one bit for extra -- for every two signal points as opposed to adding one bit for every signal point?
A. So when you look at the systems, if you look at the performance you get either coding gain or probability of error. It's all normalized to the transmitted power.
As it turns out, when you consider, for example, the four-dimensional system and you look at the signal power across the four dimensions, it's less, as I recall, by about 0.7 DB, than in a two-dimensional system.
So as Lee-Fang Wei talks about in his paper, you get an additional gain from the fact that you need less power to get the same error rate, or, for the same power you get improved performance, you get more coding gain.
Q. Can you quantify this coding gain achieved?
A. I just said, in the example of Lee-Fang Wei, as I recall -- maybe I should read it again --

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but I think it was about 0.7 DB.

Q. In your opinion is that a significant gain?

A. Significant enough to become part of a standard.

Q. Part of which standard?

A. V.34.

Q. Is that standard still employed today?

A. It's a valid standard.

Q. What is the V.34 standard?

A. It's a high-speed modem with rates for the PSTM, Public Switch Telephone Network, of rates. I think it goes up to 33.6 kilobits per second.

Q. Are there modems employed today that still operate at those data feeds?

A. Sure.

Q. What would be an example of it?

A. I think people -- people are still selling them. The chip vendors.

Q. Go ahead.

A. When you need dialed access to a network, that's the most reliable means now of communicating. Wire line access.

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Q. And those systems use 33.6 kilobits per second?

A. I think that's the high speed. Maybe 33.4 or 33.6. That's the speed of the V.34 system.

Q. What are the disadvantages of using -- of adding one bit for every two signal points as opposed to adding one bit for every signal point?

You mentioned that one advantage is coding gain. What are the disadvantages, that you can think of?

A. I can't think of any.

Q. What about the error correcting capability, wouldn't that be decreased?

A. Not -- the overall coding gain is improved by 0.7 DB. That means the error capability is improved.

Q. So the coding gain encompasses the error correcting capability of a decoder?

A. You look at a system, what you put in, what you get out, how much transmitted power you put in, and you look at the error rate. That's what you compare.

Q. What about in data systems where you need to transfer a significant amount of data an

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unlimited time period? Would you still use this system of adding one bit for every two signal points?

MR. TROPP: Objection.

A. I mean, you're asking a question, which is, what are the constraints. I'd get myself a fiber and transmit a couple of gigabits.

Q. My question is how is this -- would this coding gain differ in other applications? Other than the V.34?

A. I mean, the coding gain -- V.34 is a particular system which has all sorts of parameters. And if you look at other systems, you could compare -- you typically compare the transmitted power that you get -- that you produce, and you plot the error rate, and you compare a suite of systems, uncoded, various kinds of coding, and you just look which performs better.

Q. Have you considered these other systems and have you calculated their coding gain?

A. I have no idea what you're asking me.

Q. Well, you mentioned there are other systems other than the V.34 standard. You're also stating that Mr. Wei came up with a coding gain of

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0.7 DB using the V.34 system.

What I'm asking you is whether you were able to quantify the coding gain in other systems?

A. Me? Or people in the art?

Q. You and the people in the art.

A. This is a mature business. You look at the IEEE transactions on communications theory, there are IEEE transactions on communications, there are hundreds, if not thousands, of papers on coding, on various systems, wire line, wireless. Just an abundance of results and improvements.

I mean -- but at the time of the patent and the time that Wei wrote this, this was the best in the world.

Q. Is it possible that today a system would be able to employ the Wei method of adding one extra bit for every two signal points and achieve a lower coding gain than with a system where one bit is added for every signal point?

A. I don't understand your question.

The evidence is V.34 is a system and uses the ways of teachings or patent technology. I'm not sure -- that's a fact. So I don't understand your question.

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Q. Your conclusion at the end of paragraph 23 is based entirely on Wei's results, on results of the Wei reference; is that correct?

A. I mean, if you look at the efficiency, one could look intuitively, saying that you're only adding one extra bit for every two signaling points for -- than adding one for every signaling point. So you have to transmit -- on average the redundancy is 0.5 bits.

Q. But you also --

A. Then I said that's looking at it from the -- let's say -- what's going into the system.

The practical -- to me -- aspect that you measure is you get improved performance in terms of improved error rate. Or for a given error you can run at a lower transmit power.

And Wei was the first, in my mind, to do this. But there were many people who came after this in looking at this.

Q. You mentioned that the redundancy is increased -- I'm sorry.

You mentioned that redundancy is decreased by adding less bits, and, therefore, that improves the signal to noise ratio.

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A. I mean, at one level you can say it's an easier job for the transmission system because it only has 0.5 bits of redundancy for a two-dimensional point.

But if you really want to understand this you have to get into the mathematics of four-dimensional signals.

So Wei's paper, in our book we describe it -- the chapter that I wrote was based a lot on Lee-Fang Wei's work, and he goes through and he calculates the savings in transmit power.

Q. And you agree that Wei's reference only considers the V.34 system for his conclusion?

A. Looking at the information theory paper?

Q. Yes.

(The witness reads document.)

A. I believe when Wei wrote this V.34 wasn't finalized, and this led to his paper and the -- he refers to the base case of V.32, which is a two-dimensional trellis coder.

I mean, this is a generic scientific paper. You could apply this to lots of wireless systems, for example.

It happened to be adopted as a standard

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for wire line modems. But this is, you know, a substantial piece of work.

Q. Has anybody adopted the Wei's findings and the Wei's systems, other than in V.34? What other application of Wei's system can you think of?

A. I -- let me look more -- I mean, nothing comes to mind, but that doesn't mean that they haven't been used in other systems. So I -- I haven't devoted any effort to search that out.

Q. Sitting here today you can't think of any systems that employ Wei's --

A. The original V.56 modem was PCM downstream and Wei upstream. So V.56 standard.

Q. Okay. V.56 standard.

A. Right.

Q. Any other applications that you can think of?

A. That's -- that's a big one. People are making billions on the V.56 modem today. Billions of dollars.

Q. But --

A. I won't comment anymore. Nothing else leaps to mind. But I reserve judgment to say I haven't thought much about that.

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Q. Can we agree that redundancy that is decreased is offset by the error correction capability by the receiver? While the transmitter's job is easier because it processes less data, the receiver on the other hand is not able to decode the encoded data as well?

A. I don't understand the question.

Q. In general, doesn't the decrease in redundancy of bits lead to decrease in error correcting capability?

A. Absolutely not. Contrary. This system has improved performance. That's why it's so powerful. That's why he became a celebrity.

With his 4D system you get improved performance as measured by error rate for the same amount of signal power. That's why it became a standard. If it didn't, I don't how it would become a standard.

Q. You spoke about state transitions and you equated one state transition to one expansion; is that correct?

A. I said the way the system works when you have a state transition, it produces an expanded set of bits, yes. In figure -- in page 5 in my

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declaration.

Q. And you concluded that one set of bits is expanded to produce an output set of bits during one state transition and through one expansion?

A. You would have to repeat that. I think you asked -- the front end is too loaded for me to parse. Could you ask me a similar question, or...?

Q. One set of bits is expanded in to produce an output set of bits, and that occurs during one state transition and one expansion?

A. Let me say it my way:

You have an input. You have a state machine. The state machine cycles. It produces an expanded set of bits.

Q. And it produces the expanded set of bits in one cycle?

A. Of the machine?

Q. The machine.

A. Of the machine.

Q. Other than the figure on page 5, can a trellis encoder be designed to perform state transitions in other ways?

A. I -- I don't understand the question.

Q. Does -- can you design a trellis encoder

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where one state transition leads to more than one expansion?

A. That's not what -- the way a trellis coder operates. I am not aware of anything.

I think I explained many times, trellis encoder cycles through one state transition, produces an expanded set of bits. That's the way a trellis coder operates.

Q. Can it produce several expanded group of bits in one cycle of the machine?

A. It produces one expanded set of bits that, then, could be mapped -- if it's 2N-dimensional those bits will then be mapped over N signaling intervals. That's the way -- that's the way a multi-dimensional trellis coder works.

Q. And when you produce this expanded group of bits, could that expansion add more than one bit?

A. It's not the way that I typically think of it, but in Wei's last paragraph he suggests that you could.

Q. Is it your opinion that it is possible?

A. To do what?

Q. Do you have an opinion as to whether

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this is possible?

A. What's possible?

Q. To design a trellis encoder that can add more than one bit during one expansion.

A. I have no opinion right now.

THE WITNESS: Is it possible to have a break soon?

MR. KOLMYKOV: Sure. Right now.

THE VIDEO OPERATOR: The time is 3:28 p.m., and we're going off the record.

(A recess was taken.)

THE VIDEO OPERATOR: The time is 3:38 p.m., and we're back on the record.

BY MR. KOLMYKOV:

Q. On the receiver end, how is the trellis-encoded signal decoded?

A. So you have a front-end receiver and you do some processing and filtering and you have an I and Q rail for -- in the QAM context, and the trellis decoder basically runs the Viterbi algorithm.

And what I mean is at the transmitter, if you have a trellis diagram which has the evolution of the state machine of the encoder,

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evolution state of the coder, the receiver tries to estimate the path that the transmitter state machine took.

And so -- and then when it does that -- there's various technicalities of how it does it and how it short-circuits it and expedites it. But then when it gets to state, it then goes back and looks at the sample to determine which of the points -- so the state relates to the subsets, and then when you identify the subsets, most likely sequence of subsets, you then go back and look at the received signal point, or points if it's four-dimensional, you have to look at pairs of these, and you decide which of the points within a subset has been transmitted.

Q. And the trellis decoder that performs an Viterbi algorithm, can we call a Viterbi decoder?

A. A Viterbi decoder is a generic term. People would refer to it -- I perhaps refer to it sometimes as a Viterbi decoder.

It's also known as an MLSE, maximum likelihood sequence estimator.

It uses the Viterbi algorithm to try and get the best estimate of the sequence of states

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that the transmitter went through. That's its job.

Q. Okay.

And you mentioned that a Viterbi decoder estimates -- attempts to estimate a path that the trellis encoder took; is that correct?

A. Yes. At the transfer.

Q. When it estimates this path, does the Viterbi decoder accumulate a certain value?

A. I don't know how deeply you want me to go, but what you're doing, suppose you have a -- there's a confusing -- not confusing, but a notation of state versus dimensionality. The state is two to the number of shift registers.

So let's consider a four state trellis encoder.

And it takes you -- based upon the input, and it drools, it goes through a unique path.

At the receiver, the way dynamic programming works is you're -- at any state that you're at -- I'm sorry, at any point in time, you keep the most likely path for each of the four states looking back in time.

So Viterbi algorithm uses something

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called backward dynamic programming. You associate a metric with each of those paths called likelihood, or accumulated likelihood.

So based upon the likelihood where you came from on that path, and what you receive in the way of signal sample, you update the likelihood.

The -- in a modem, the -- this maximum likelihood sequence estimation, if you keep sending bits indefinitely, which would be the nominal case, you could go on and on and say where are my bits. You haven't made a decision.

And there's something called a merge. If you look back, let's say in this four state system, you have four paths. With high probability, those four paths will go through a common node at some point in the past. And so one could say no matter what happens in the future, that node and the path -- that's called a merge -- and back to the previous merge, that's part of a maximum likelihood path, no matter what happens in the future.

That's the charm of the Viterbi algorithm. I like the subject.

So the Viterbi algorithm, the reason why

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it's useful, the complexity is proportional to some constant times time.

The alternative, if you didn't use this, you would have an exponent after 10 symbols, and if there were four possibilities you would have four to the tenth possible things to evaluate, and if 10 goes to 100 you couldn't possibly do it.

The reason Viterbi became a celebrity, he developed this algorithm originally for convolutional codes that's been used for trellis decoders.

That's the way a trellis decoder works.

Q. Thank you for that long explanation. It's been very helpful.

So it's true there is a path metric that keeps updating in the Viterbi decoder?

A. In the four states. There are four path metrics.

Q. Okay, four path metrics?

A. In a four state machine.

Q. In a four state machine there are four path metrics that are all being updated upon reception of signal points.

Is that a yes?

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A. Yeah. If you have -- for example, if you have now a four-dimensional system, which -- so the number of states and number of dimensions could be chosen independently, you -- in a four-dimensional system it means you're going to process two received samples at a time to do the update of the metric. Because one state transition produced two transmitted symbols. Therefore, at the receiver you will gather together two received samples: I and Q, and an I and Q again.

And that's what you'll need to compute your metric.

Q. Can a Viterbi decoder start calculating the path metric upon reception of one signal point?

MR. TROPP: Objection.

A. What type of system?

Q. Let's call it four-dimensional system with a channel symbol constituting two signal points.

A. No. As I just said, you need -- you couldn't begin processing until you had two of the samples.

Q. Why is that? You did mention before that the path metric is being estimated. And it is

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being estimated signal point by signal point.

A. I didn't say that. I said a time instant -- when you update the path metric.

So if you look at the transmitter every -- what you want to do is emulate or estimate the transitions that the transmitter goes through at the receiver.

Every time there's a state transition in the four-dimensional system, what does it do? It produces ultimately two signal points, two two-dimensional signal points.

So obviously -- or clearly -- at the receiver you would want to gather these two corresponding signal samples to start building your metric processor.

Q. Okay. Let's assume we have a system with four one-dimensional signal points constituting a channel symbol.

Does the Viterbi decoder have to receive all four signal points to start calculating the path metric?

A. Let me -- what I heard was you had one-dimensional signal point.

Q. Uh-hum.

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A. A four-dimensional trellis encoder.

Q. Yes.

A. So each state transition produced four signal points that were sequentially transmitted over four signaling intervals.

That was the context you're asking me?

Q. Yes.

A. Then you would have to wait for four received samples to begin.

Q. Now, let's assume we use a trellis encoder of a different rate, N over N plus 3.

How many -- does the Viterbi decoder still have to receive all signal points?

MR. TROPP: Objection.

A. From what you told me I couldn't answer the question because you didn't tell me what the dimensionality dash.

Q. Same dimensionality.

Let's assume we have a one-dimensional signal point and four of these one-dimensional signaling points constitute a four-dimensional channel symbol.

If a trellis encoder is a rate N over N plus 3, then it generates four bits for every one

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input bit, would a Viterbi decoder still need to receive all signal points before it starts processing and calculating the value of the channel symbol?

MR. TROPP: Objection.

A. I think you -- let me go back to what you said.

You said "N over N plus 3." So what's N?

Q. N is the input bit.

A. So -- I thought you said that you get three outputs in one input. Maybe I misunderstood you. I didn't understand the question.

Q. No. For every input you get -- for every input bit you get four output bits?

A. So therefore N must be equal to 1.

Q. Yes.

A. That's what I asked you, and you said no.

Q. I apologize. Let me rephrase the question. Let me ask you a general question.

Is it possible to envision a trellis encoder and decode a pair where the Viterbi decoder does not need to receive two -- both of the signal

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points constituting a channel symbol before it starts calculating the value of a channel symbol?

MR. JUISTER: Objection.

MR. KOLMYKOV: Is there one attorney or two attorneys?

MR. TROPP: There are multiple parties in the case and there are four attorneys in the room and you heard an objection from one of them.

MR. KOLMYKOV: You can't have four attorneys defending one witness.

MR. TROPP: As a practical matter, there are four Defendants represented here today by attorneys, and each and every one of us is entitled to make objections. No one is representing the witness.

MR. KOLMYKOV: How many people have a microphone in this room?

MR. TROPP: I don't understand the relevance of the question. Did your notice not invite Defendants to attend and cross-examine? I assume you contemplated that Defendants would appear and would not be potted plants.

MR. KOLMYKOV: From my experience, four attorneys cannot defend one witness.

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MR. TROPP: If four attorneys represented the same party you would be perhaps correct. But here we each have our own separate interests and we're entitled to make our own separate records.

MR. KOLMYKOV: I'll leave that issue open to discussion.

BY MR. KOLMYKOV:

Q. Let's turn to column 8, pages 47 to 50, of the '627 patent.

MR. TROPP: I'm sorry, what columns of the '627?

MR. KOLMYKOV: 47 through 50.

MR. TROPP: Thank you.

Q. I will read it into the record.

"Without having received all of the signal points of a channel symbol, one cannot take advantage of the accumulated path metric information, but, rather must rely on the so-called raw sliced values, which is less accurate."

Doesn't this statement imply that the path metric is already being accumulated upon reception of a single signal point?

A. You can build suboptimum receivers in

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many ways. As he says, "which is less accurate." You can build lots of less accurate receivers. He makes that comment. Okay.

Q. So it is possible to build a receiver that will process one signal point at a time?

MR. TROPP: Objection.

A. It's always possible to build a receiver. Whether it's useful or not remains to be seen.

Q. When the Viterbi decoder receives one signal point what does it do?

MR. TROPP: Objection.

A. What type of system?

Q. Let's say we have a four-dimensional system on the '627 patent.

A. There are many ways to implement procedures. So in my experience it waits for the second sample. And then in each of the states it looks back and calculates the accumulated path metric between the received signal samples of the two intervals and the quantities that it's going to be compared with for each of the state transitions.

Q. What if it doesn't wait, and starts calculating that distance between a signal point

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that's available in the alphabet and the signal point that's received?

A. You know, I haven't looked at this in detail, but to do it correctly you need both samples to get the result that you're going to update. You may do something preliminary, but...

Q. Let's look at the Wei patent, which is on page D 62. It's part of your declaration.

I said D 0062, right?

A. No.

Q. Let's look at column 3, line 51.

It reads that: "A decoder, 48, feeds back preliminary decisions on the received coordinate pairs to equalizer/demodulator updating signal calculator, 45. These preliminary decisions are processed and calculated, 45, in a conventional manner to generate updating signals for the equalizer and the modulator."

Wouldn't it be fair to say that the decoder calculates preliminary decisions based on the reception of one coordinate pair?

MR. TROPP: Objection.

A. So if you read this for updating for the equalizer and the demodulator as disclosed in

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Falconer's celebrated paper, the problem is the following: The demodulator is tracking a very fast changing quantity. Let's say phase (inaudible).

It has to be responsive to something which is changing faster than any other impairment in the system.

So it has no choice but to do what it can and take preliminary decisions to update the phase tracker. The alternative would be for it to go on pause, wait until the Viterbi decoder produced the symbols, now update the phase.

But that correction would be ancient history relative to the demodulator.

So it's a -- I was involved in the problems. I understand the architecture very well.

So what is being referred to is when you have a coded system which has long delays relative to signaling intervals and you have a fast changing channel impairment that's changing quickly over signal interval, the preferred method is to do what you can, make a preliminary decision of the received sample, slice it, assume that's correct -- but it may not be; likely it will not be -- use it to update the demodulator, and that's the way the

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system works.

Q. And the preliminary decision you just described is based on the reception of one signal point?

A. It's not used for the trellis decoder. It's used for the phase lock loop for the demodulator. It is not used in the Viterbi decoder. As I understand it.

Q. The sentence reads: "The decoder feeds back preliminary decisions."

So it is the decoder that --

MR. TROPP: Objection. That's not how the sentence reads.

Q. -- makes preliminary decisions?

A. Which line are you on. I lost you.

Q. 51 of column 3.

(The witness reads document.)

A. Preliminary decisions, not final decisions.

Q. By "preliminary decisions," that means it starts calculating some type of metric?

A. But it's not used -- that feedback, what's fed back may not bear much relation to the ultimate decisions that that receiver makes.

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Q. Okay. I understand that.

But can you answer my question? The de -- does the decoder in the Wei reference that you used to support your declaration, does make preliminary decisions based on reception of one coordinate pair?

MR. TROPP: Objection.

A. I prefer to say that it uses the preliminary decisions for updating the phase lock loop in the demodulator. That's what it does in these preliminary decisions.

Q. Does that sentence say that?

A. I know how this works. I have been involved in designing the systems. That's the way it works.

Q. But wouldn't you agree that it is possible to design a receiver where the decoder starts calculating the path metric based on a reception of just one signal point?

MR. TROPP: Objection.

A. As I said, in a multi-dimensional system, the preferred way -- the preferred means is to process the samples associated with the number of samples that were produced from the output of

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the state transition.

One can build receivers in many ways. You know, you could build receivers, you could build bad receivers. It's possible to do almost anything.

Q. So the answer to my question is yes, it is possible?

A. I wouldn't guarantee the performance. So I prefer to say you can do what you want. If you want to achieve the proper performance, you will need to gather the information from these two signal samples and, you know -- engineers always experiment with suboptimum means and other approaches -- you know.

Q. Can we go to paragraph 24 of your declaration.

In paragraph 24 --

A. Can I read it, please?

Q. Sure. I'll give you...

(The witness reads document.)

A. I've read paragraph 24.

Q. You describe in paragraph 24 interdependency among signal points belonging to a multi-dimensional channel symbol that results from

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a single state transition.

Is that correct?

A. Yes.

Q. Could you please explain this interdependency, and how it does result from this single state transition?

A. When -- in a four-dimensional system you have a single state transition that will specify two subsets. And which two subsets are specified are related because they are produced by the same state machine.

Q. How does the fact that the two sets are produced by one state machine create interdependency among these two groups of bits?

A. Well, because the state --

MR. TROPP: Objection.

THE WITNESS: I'm sorry. I'm sorry.

A. The state machine has memory. That state machine is driving -- producing those two outputs. So in general, they will be related. And they also produce -- they are produced by the same machine. So...

The principal reason that you generated in the four-dimensional example, you have two

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subsets. The subset identifiers are coming from the same inputs, the same state transitions, and it's reasonable to conclude that the subsets are related.

Q. You do differentiate between interdependency due to a single state transition and another type of dependency which you call time dependency.

What is the difference between the two dependency --

A. If you have a two-dimensional trellis encoder, if you look at the evolution of the states, consider a four state machine, you can't go -- generally you go from one state, you could only possibly go to two states. You can't go from one state to any arbitrary state.

So therefore where you were limits where you can go on the next iteration of the machine.

So that says -- in fact, that's the principle of encoding: You're building a structure over time. That's the dependency I was referring to.

The second level is in a multi-dimensional -- let's say a four-dimensional

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machine, every one of those transmissions produces two subsets.

So that's the second level of independence -- second level of dependence.

Q. So how does the combination of these dependencies mandate that the decoder must receive all of the signal points of a particular channel symbol?

A. Because the way you created that was from one state transition. It produced in the end two signal points. And since you're trying to emulate or estimate at the receiver the state transitions that the transmitter is going through, you need that information to give the most accurate estimate.

Q. Okay.

Does the '627 patent discuss state transitions?

A. I'm going to take some time to take a look.

MR. KOLMYKOV: We can end the tape while he's looking at the patent specification.

THE VIDEO OPERATOR: This completes Tape Number 3. The time is 4:12 p.m., and we are going

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off the record.

(A recess was taken.)

THE VIDEO OPERATOR: This is Tape Number 4. The time is 4:17 p.m., and we're back on the record.

BY MR. KOLMYKOV:

Q. I will repeat my question.

Does the '627 patent discuss state transitions anywhere in the specification?

A. I have a two-part answer.

The '627 patent talks about, on column 3, line 21, one -- in case of N equals 1, would be expanded to two bits.

That's -- I interpret this as the expansion as a result of a state transition.

I mean, this patent builds upon the prior art, the gigantic prior art of trellis encoders. So it doesn't really talk about what goes on inside a trellis encoder or decoder. The scope of the patent is on interleaving. So it's not talking about the details of the trellis encoder.

So, you know, it doesn't talk about state transitions, it talks about the outputs and

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bit expansion. And to me the bit expansion is a result of a state transition.

Q. Can we look at figure 3.

A. Of '627?

Q. Of the '627 patent.

How are the signal points between channel symbols of a trellis stage interleaved?

MR. TROPP: I'm sorry, I'm getting tired now. Can you read that back?

(Requested portion of record read.)

MR. TROPP: Objection to the form.

Maybe I'm not the only one getting tired.

A. Are you asking me to describe what the invention is or what the purported invention is?

Q. How is the interleave performed between signal points of a particular channel symbol?

A. The signal point interleaver is element 341. That does the interleaving of the signal points.

Q. How does it interleave the signal points?

A. It has a straight-through path and alternate clocks to a delay.

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So if you look at the input of the signal points, X0 alpha, X1 alpha, you see that the -- at X0 alpha is the -- at the interleaver the output is the first signal point. And X1 alpha, then, appears three points -- signal points later.

That's what it does, is cycles through the input. It -- alternatively, it delays -- alternate signal points, and this way it breaks up, let's say the alpha zero, alpha 1, beta 2, beta 3, the gamma 4, gamma 5. They don't appear adjacent in time next to each other in the stream going to the modulator.

Q. How would you describe a function of interleaving generally, without looking at the '627 patent?

A. The purpose of the interleaver is to take signal samples or signal points that occur sequentially in time and distribute them over a time interval so that they are no longer adjacent to each other in time.

The simplest way to think of it is you have an input stream that I read into a matrix. I keep cycling around the matrix and I read out the columns.

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So I cycle in through the inputs on the rows and I read out the columns. That's a classic form of block interleaver. This is a different kind of interleaver here.

Q. We would agree that one implementation of an interleaver would have a delay element of some sort?

A. Yes.

Q. Can we agree that another form of an interleaver could include a switching mechanism of some sort?

A. I mean, in '625 patent, that's what Betts proposes in a generic sense in '625. He has a switching circuit that distributes inputs to trellis coders and then reads out of them sequentially. So that accomplishes that purpose.

Q. What is the result of the '625 patent? Am I correct to say that the channel symbols are interleaved?

A. The channel symbols are interleaved. It doesn't, to my reading, that it doesn't talk about the dimensionality of the trellis encoder.

Q. And the channel symbols are interleaved using a switching circuit?

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A. A commutator or switching circuit or whatever you want to call it.

Q. If we look at claim 1 of the '627 patent starting with line 15 -- you should obviously read the entire claim, but I would like you to pay attention to line 15, starting with line 15.

(The witness reads document.)

Q. Would you agree with me --

A. I have to read it.

Q. I'm sorry.

A. I'm a slow reader.

(The witness reads document.)

A. I read the claim.

Q. So starting with line 15, would you agree with me that claim 1 requires interleaving to be performed in two ways?

(The witness reads document.)

MR. TROPP: Objection.

A. The way I interpret the claim is that you have a system like Betts describes in '625, which is generic, and now it's dealing with the plurality of signal points that is a multi-dimensional trellis-coded symbol. He recognized that these signals are dependent and he

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puts the additional signal point interleaver in the system.

That's, as I understand, that's what the claim refers to.

Q. Well, the claim reads: "The interleaving being carried out in such a way that signal points of each channel symbol are nonadjacent and such that the signal points of adjacent symbols in any one of such channel symbol streams are nonadjacent."

So would you agree these are the two ways of interleaving --

A. Let me read it again, please.

(The witness reads document.)

A. He achieves two desired goals. So -- I mean, the claim is that he's able to achieve -- meet both his requirements.

Q. Okay.

And one of those requirements is achieved using a switching circuit of 337? Does that look true?

A. Oh, 331 and 337, the input.

Q. Okay.

A. The way -- the way he does it, he is

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interleaving there the subset identifiers. That's what that interleaver is doing.
Q. Okay. But that interleaving is what enables the invention to achieve the desired result?
MR. TROPP: Objection.
Q. The result being the channel symbols are interleaved as well as the signal points within those channel symbols are interleaved.
MR. TROPP: Same objection.
A. The switching circuit then still maintains, if you look at it -- at the output of the switching circuit you have X0 alpha, X1 alpha, right next to each other, and then he uses 341 to interleave those.
MR. JUISTER: What figure are you looking at?
THE WITNESS: I'm looking at figure 3 of '627.
Q. Okay. And can we agree that the functions performed by the switching circuit as well as the interleaver can be performed in one device using software?
A. When you say -- I mean, "one device"?

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What do you mean?
Q. I mean one digital signal processor.
A. I mean, that's -- you could probably build a whole receiver on one DSP.
Q. And these functions of signal point interleaver 341 as well as the switching circuit 337 and the 4D QAM encoder can all be written in software?
A. As I said before, it depends upon the clock speed, the capacity of a DSP, relative to the information rates and the number of operations.
Q. But if all those numbers are satisfactory, you could write software that would perform all these functions?
A. Yes. That's generally the way these systems are built today with DSP software.
Q. Okay. Thank you.
On the receiver side, if we move to figure 4, you would agree that the signal point interleaver and the switching is your circuit for 56, they perform --
A. I'm --
Q. I'm sorry, not switching -- the signal point interleaver, 441, and the switching circuit,

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431, perform the opposite function of what was done in the trellis -- in the transmitter stage?
(The witness reviews document.)
A. You said 441 and 431?
Q. Yes.
A. They do the deinterleaving.
Q. And similarly, a receiver could implement a digital signal processing chip that performs both of these functions (indicating) via software?
A. Yeah. Depending on the speed, you could write it in software. If the thing is running slow enough you could write this on a general purpose process. Software is software. It only works on the general speed device and the speed at which you're operating.
Q. Okay, thank you.
If you look at figure 3 again, is it possible to design a transmitter to achieve the resulting output differently from what's depicted in figure 3 (indicating)?
A. You mean, starting with the input bits and producing the output?
Q. Yes.

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A. I wouldn't -- I wouldn't venture an opinion on that right now.
Q. For example, could you put a signal point interleaver, 341, prior to the 4D QAM encoder, and still achieve the same result?
A. Where would you put it?
Q. You would put it, for example, on line 338.
A. Well, the way he has it, 338, what you have there are indices you don't have signal points. So the signal point interleaver -- I mean -- it's a signal point interleaver. You don't have signal points at that point.
Q. I understand that.
But let's assume we're only interested in producing the result on 3 -- on line 342.
Are you with me?
A. No. Oh, okay. 342.
Q. To produce this result, if we were to put an interleaver, 341, on line 338, and the interleaver would interleave the subset identifiers, would the same result be produced?
A. I would say at a minimum you would have to put 341 on line 17 as well as 363. If you want

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to do interleaver -- on line 317. You want to do interleaving of the uncoded bits as well. Otherwise you would be out of cycle.

Q. So you could put 341 on lines 317 and 338 and still achieve the result on line 342?

A. We're talking here in a functional level?

Q. Yeah, on a functional level.

A. This is a functional diagram. So -- and you -- the terminology, it's no longer a signal point interleaver, it's a signal-something interleaver, because it's not dealing with signal points.

Q. Okay. Let's call it just an interleaver.

So an interleaver would be placed on lines 317 and line 338 to produce the same result as required by the patent on line 342?

A. I have to think about it, if it's exactly the same result. But -- so let me just think about it. I don't want to go any further with this now.

Q. But you stated that it is possible to produce the same result if you were to place an

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interleaver in another location?

A. I didn't say that.

MR. TROPP: Again, he just actually specifically refused to go there, which brings the point that we're again beyond the scope of the declaration. So I'm wondering again where you're going. And when you're planning to get there.

MR. KOLMYKOV: Do I hear an objection?

MR. JUISTER: That certainly was an objection.

MR. TROPP: You've heard the start of a colloquy. I'm not objecting to the form of the question. I am asking whether you are going to abide by the agreement coming in that this is going to be a deposition that, with defined exceptions, were limited to the scope of the declaration, and it seems to me you're beyond it.

MR. KOLMYKOV: My understanding the deposition was limited to claim construction issues.

MR. TROPP: That are raised in the declaration.

MR. KOLMYKOV: That was not my understanding.

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MR. TROPP: This gentleman isn't here to offer random opinions on issues he hadn't considered.

He's here to tell you about the declaration, which is the reason you requested to have the opportunity for the deposition.

And we've been going all day and I have not yet prevented you from asking a question that you wanted to ask. But when the witness has said to you, I don't have an opinion on that and I would want to think about it, and I tell you it's beyond the scope of his declaration, I think it's fair to say where are you going and when do you plan to get there, rather than to have you ask another question of the witness in which you ask him to agree to say something that he hasn't said.

MR. KOLMYKOV: Are you finished with the objection?

MR. TROPP: Again, it's a colloquy.

MR. KOLMYKOV: I don't see a need to respond to your statement.

MR. TROPP: That is fine. Again, I'll take each statement one at a time, then.

MR. KOLMYKOV: I'll continue with my

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questions.

BY MR. KOLMYKOV:

Q. You referred to the Betts '625 patent. It starts on page D 0098 of your declaration.

Does the '625 patent mention anything about signal points?

A. I'm not -- I'm going to have go through it. If you would like me to spend the time to go through it, I would be glad to do it.

Do you want me to spend the time and read it now?

Q. No, that's okay.

You did read the '625 patent in its entirety?

A. I looked at it. This was the patent that was provided to me by counsel. And I looked at this as it's prior art to '627. I didn't study it in great detail.

Q. So sitting here today you can't recollect whether the '625 mentions signal points at all?

A. I would be glad to look through it. But -- I would be glad to read it again.

Q. We did establish that the '625

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interleaves channel symbols; is that correct?

A. The '625 -- when I look at figure 1, it takes the data, distributes it among -- let's say in that example -- four trellis encoders. It takes the output of the trellis encoder -- this patent as, far as I can recall, doesn't distinguish whether it's a 2D or a 2N trellis encoder. I think it's generic. And it interleaves the outputs of the trellis encoders.

Q. Isn't an output of one trellis encoder called a channel symbol?

A. Well, I mean in his diagram he then takes the switching circuit, puts it to a QAM encoder and a QAM modulator. So there's not enough detail for me to say -- here to say I have an output of a trellis encoder.

In the construct here it's a QAM system, so I'm assuming at each time you're producing a signal point that sits in two dimensions. If this is a -- a 2D trellis encoder.

Q. Why do you feel inclined to limit the most general case to a 2N-dimensional signaling scheme as opposed to any dimension signaling scheme?

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MR. TROPP: Objection.

A. Which patent are you talking about?

Q. I'm referring to the '625 and the '627.

(The witness reviews document.)

A. I mean, if I read just the abstract at '625, and the transmitter of a data communication system using QAM, that tells me that the constituent signal points are two-dimensional.

Q. In a 2N-dimensional signaling scheme, what does N again refer to?

A. We're talking about a trellis coding.

Q. Yes.

A. So the 2 refers to the constituent -- the signal points are two-dimensional. N refers to the number of output points that are produced by one state transition.

So, for example, a 4D system is two I and Q points.

Q. Let's move back to figure 3.

MR. TROPP: Of '627?

Q. Of the '627 patent.

The multiple trellis encoders, 319 alpha, 319 beta and 319 gamma, together with the switching circuit and the 4D QAM encoder, generate

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interleave channel symbols.

Is that correct?

A. The -- what you have is signal points at the -- on line 325.

Q. But the signal points constitute channel symbols; is that correct?

A. In the language that we've used in the patent, a trellis-coded channel symbol for this four-dimensional system, for example, is X0 of alpha and X1 of alpha, because the state transition produces those two signal points. So that's an entity.

Q. Okay. So there are signal points on line 325. Is that correct?

A. I -- I didn't understand the question.

Q. So there are signal points on line 325, is that correct?

A. Yes.

Q. Would it be fair to say that the signal points are interleaved by the switching circuit, 337?

A. The 337 takes the output -- does interleaving, but it's still treating the pair -- in this case -- of subset indices at one entity.

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So it accomplishes an interleaving of one kind that the inputs in time are separated. But the outputs are still -- have adjacency in terms of the two signal points that are produced for each state transition.

As I understand it, that's what the claimed invention is. Then to deal -- that's as far as I can tell. That's all prior art.

The invention is using the signal point interleaver, the claimed invention.

Q. Now, if we refer back to claim 1, "means for interleaving the signal points of said generated channel symbols."

Do you see that?

A. Yes.

Q. But it doesn't say interleaving the signal points of a channel symbol.

MR. TROPP: We're again beyond the scope of the declaration. He's offered no opinions on the means plus function term, means for interleaving.

MR. KOLMYKOV: I'm not interested in his interpretation of a means plus function term.

MR. TROPP: I'm sorry, perhaps I

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misunderstood your question.
MR. KOLMYKOV: I'm interested in his --
BY MR. KOLMYKOV:
Q. When the claim says "interleaving the signal points of channel symbols," what does that mean to you?
(The witness reads document.)
A. Can you ask me the question again?
Q. What does it mean to interleave signal points of channel symbols?
A. So if I look at line 325, the trellis coded symbol that's produced, let's say of the output -- coming from the alpha trellis coder, is the pair of signal points, X0 superscript alpha, X1 superscript alpha.
And that's the signal -- together that's a trellis-coded channel symbol. And it talks about performing interleaving to separate these in time so that they are nonadjacent.
Q. Is it possible to -- strike that.
What is the result on line 342?
A. I don't know what you mean by "the result."
Q. Is it -- would you agree that it's a

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combination of interleaved channel symbols as well as interleaved signal points within those channel symbols?
(The witness reviews document.)
A. I mean, the two stages of interleaving interleaves the symbols, and the symbols have constituent two signal points which are then interleaved by 341.
Q. Could we achieve the result of the interleaved channel symbols and the interleaved signal points from one operation of the encoder, 324?
MR. TROPP: Objection.
Q. Without the signal point interleaver 341?
A. I'm sorry, I don't see 324.
MR. TROPP: It's the QAM encoder.
MR. KOLMYKOV: Let me rephrase that question.
Q. Is it possible to interleave the channel symbols and the signal points within those channel symbols at the same time?
A. I think this is the same question you asked me before, and I'm not prepared to comment on

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various permutations of this system. I haven't studied it in that great detail. So I won't comment. I have no opinion right now.
Q. What is the point of separating the adjacent signal points?
A. The -- almost all of the systems are -- their performance degrades when you have a burst of noise. So the purpose of interleaving is to separate as much as you can in time of all the, let's say, signal points that have been produced by the same mechanism.
So the notion is to separate -- here we have a four-dimensional system that produces two outputs. So in addition -- two output signal points. You would want to separate those, so that if the noise persisted over one or two intervals it would appear -- it would appear to the receiver as an isolated noise burst and isolate the noise.
That's the purpose of interleaving in general.
Q. Okay. Can you look at figure 5 of the '627, line 3.
THE WITNESS: Can I take a break?
MR. KOLMYKOV: Yeah, sure.

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THE VIDEO OPERATOR: The time is 4:57 p.m., and we're going off the record.
(A recess was taken.)
THE VIDEO OPERATOR: The time is 5:06 p.m., and we're back on the record.
BY MR. KOLMYKOV:
Q. So as we look at line 3 of figure 5 of the '627 patent, it depicts an output where there is an interleaving that's occurring, but only one trellis encoder is employed.
Do you see that?
A. So Roman III interleaved one trellis stage. Just alpha.
Q. Yes. As you know, while the signal points X0 alpha and X1 alpha are separated by three intervals, the signal points X1 alpha and X 4 alpha are not separated.
Do you see that?
(The witness reviews document.)
A. I'm just looking at the sequence, X1 and X alpha.
Q. But you see that X1 alpha and X4 alpha are not separated through simply interleaving the signal points of the trellis-encoded channel symbol

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stream?

A. Which is the interleaver that's referred to here?

Q. It refers to an interleaver as depicted in figure 3, number 341, designated as 341.

(The witness reviews document.)

A. By one trellis stage, does that mean one trellis encoder?

Q. Yes. That's what it means. It means, instead of alpha, beta, gamma encoders, you only have, let's say, alpha.

A. Yes.

Q. Trellis encoder. So you see that X1 alpha and X4 alpha come from the same encoder?

A. Well, there's only one encoder.

Q. I apologize. It is gating late. I meant to refer to line 4.

A. Oh.

MR. TROPP: Do you want to start again?

Q. If you employ two trellis stages, X1 alpha and X4 alpha, coming out of the same encoder, are still not separated.

Do you see that?

A. And this is produced -- this is alpha

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and beta going through 341?

Q. Yes.

A. You know, I can check the math, but I don't know if there's any corrections to the patent, so I have no reason to believe that that sequence is not correct, but I haven't checked it myself.

Q. Okay. But the idea behind demonstrating line 4 output versus line 5 output is to show that X1 alpha and X4 alpha are still unseparated, which is --

A. In line 5?

Q. I'm comparing line 4 to line 5.

A. I see the X1 alpha next to the X4 gamma.

Q. And that's true, that's in line 5. That is the output of the system as depicted in figure 3.

However, if there were only two trellis stages employed, the output would be as it looks -- as it is illustrated on line 4 of figure 5 (indicating).

MR. TROPP: Is there a question? And my question is: What does this have to do with his declaration?

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MR. KOLMYKOV: I just want him to follow my logic here. And follow the drawing.

MR. TROPP: Okay. What's your question?

MR. KOLMYKOV: I could ask him questions in a vacuum, but it won't make sense.

MR. TROPP: What is your question?

BY MR. KOLMYKOV:

Q. My question is whether you would agree that in order to generate an output on line 342 you need to do -- you need to have both the plurality of the trellis encoders as well as a signal point interleaver.

In other words, you cannot produce this output simply through interleaver 341 without employing multiple trellis encoders?

MR. TROPP: Objection.

MR. JUISTER: What output? There's five outputs.

MR. KOLMYKOV: The output on 342.

THE WITNESS: Figure 3.

A. As I said before, I am not going to speculate if there's a different architecture that can achieve that output. I haven't, you know -- I can't say that some clever person couldn't do it a

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different way. So I'm not prepared now to give an opinion.

(Discussion off the record.)

Q. The reason I'm asking this series of questions is because you have an entire section in your declaration dedicated to interleaving, and it starts on page D 0013.

A. Right.

Q. And we discussed the Gallager reference which you are drawing -- a section of which you illustrate on page 13 of your declaration, as well as you go on further in paragraph 27 and paragraph 28, you state that: "The signal point interleaver, 341, uses a derailment, 3411, to separate the adjacent interdependent two-dimensional signal points on line 325, produced by three separate 4D encoders, alpha, beta and gamma."

My question to you is: In order to produce this stream of trellis-encoded and interleaved signal points on line 342, would you also need a plurality of trellis encoders in addition to a signal point interleaver as well as the switching circuit 337?

A. What I'm doing in my report is reporting

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on what the claimed invention is. That's what I'm reporting. Or declaring or commenting on. That's all I'm doing.
Q. Okay. You do talk about a signal point interleaver 341 performing a function of interleaving of signal points; is that correct?
A. Yes.
Q. In order to perform this function of interleaving signal points you must receive an interleaved stream of trellis-encoded channel symbols; is that correct?
A. As I said before, if the desired goal is to achieve a signal which looks like that appears on 342, there may be other ways to achieve it. And I'm not going to comment on that. I said that before. You asked me a similar question.
Q. Well, we talked about what are the signal point interleavers 341 can be placed before the QAM encoder, and you hesitated to answer that question.
A. That's right.
Q. However, what I'm asking you now is whether you need an interleaver, a signal point interleaver, 341, and the encoder, the QAM encoder,

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324, to produce the result on line 342?
MR. TROPP: Objection.
A. Well, that's -- that's what is produced.
Are you asking me is there another way that I could do it or what can be done? I don't have an opinion.
But what I was saying here is that in the claimed invention, in '627, is identifying the problem of the interdependency of multi-dimensional trellis-coded symbols, and it offers a way of interleaving to achieve the signal that appears on 342.
Q. In order to generate the signal points on line 325 --
A. What figure?
Q. -- of figure 3, of '627 patent, what components depicted in figure 3 do you need to employ?
(The witness reviews document.)
MR. TROPP: Objection.
A. Everything that precedes it. That's the system block diagram. That's the way it's done.
Q. So that would include the QAM encoder and the switching circuit to generate this stream

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of channel symbols on line 325, and that is what's required by the patent?
MR. TROPP: Objection.
A. This is an embodiment, and I guess this is the preferred embodiment.
Q. You're saying in the preferred embodiment you need the QAM encoder and the switching circuit to produce this stream of trellis encoded channel symbols?
MR. TROPP: Objection.
A. I think you're asking me a circular question. Here is the output of the system, and so it's produced by going through this array of alpha, beta and gamma trellis encoders, and then going -- yes, and then having the commutator switch and feed sequentially outputs to the 4D QAM encoder. That's the way the system works. That's what's described.
Q. I understand what's described.
But can you please answer my question whether the output on line 325, which is a stream of trellis-encoded channel symbols, is produced using the QAM encoder as well as the switching circuit.
MR. TROPP: Objection, and now the

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additional objection that this has been asked and answered about six times in the last ten minutes.
MR. KOLMYKOV: I didn't hear a yes-or-no answer to that.
MR. TROPP: He's answered your question six times.
MR. KOLMYKOV: He answered a different question six times.
MR. TROPP: Well, we disagree.
If you can answer his question, please do.
A. You have a switching circuit, 331. It distributes the bits through three different trellis encoders: Alpha, beta and gamma. They are four-dimensional. They produce pairs, each a state transition. A bit expansion produces through signal points. And then the switching circuit feeds these up to the 4D QAM encoder, producing a sequence that appears on line 325.
Q. So can we agree that the plurality of the trellis encoders as well as the QAM encoder generate the stream of channel symbols on line 325?
MR. TROPP: Objection.
A. I think this is the seventh time you've

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asked me that. And this is what the block diagram is. It's the preferred embodiment to generate that signal.

Q. So the answer is yes?

MR. TROPP: Same objection.

A. This is the block diagram and that's what's on line 325. It's the outputs are labeled, and that's the output that goes through these, in this case the alpha, beta, gamma trellis encoders one at a time, feeding the 4D QAM encoder, producing the 4D symbols -- two signal points associated with each trellis encoder. That's what's depicted.

Q. Okay, let me phrase the question using your terms.

In this block diagram, blocks 319 alpha, 319 beta, 319 gamma, and block 324, produce this stream, as depicted in this block diagram, as X0 alpha, X1 alpha, X2 beta, X3 beta, and so on --

MR. TROPP: Objection. Go ahead.

A. Let me add, you used the index values from the modulus converter to select the signal points. That's fed into the 4D -- as the picture shows, figure 3 shows, fed into the 4D QAM encoder

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as well, to generate the signal points.

Q. And which of these blocks in figure 3 performs the interleaving of the channel symbols?

MR. TROPP: Objection.

A. Trellis-coded channel symbols are -- there's interleaving of the trellis encoders, but that -- for a 4D system produces two signal points. So there's an additional signal point interleaver to separate holding alpha outputs from each other by at least one time instant, and the second interleaver separates the dependent points, for example X1 -- X0 and X1 alpha.

Q. What is the first interleaver that you referred to?

A. The combination of the switching circuit, 331, the three trellis encoders, and the 337, producing the output, 338.

Q. Okay. Let's refer to your CV --

A. If I can find it.

Q. -- which is the first exhibit of your declaration.

Your CV cites 89 technical papers that you published and co-published; is that correct?

A. It lists 89 papers.

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Q. Could you identify the papers that address trellis-coded modulation?

(The witness reviews document.)

A. None of these papers address trellis-coded modulation.

I think I have one or two patents of trellis coding and decision feedback. But at the time trellis came about I was a manager. I hired Lee-Fang Wei, I hired Jin-Der Wang, and some of the other references, and I was responsible for managing this, and ultimately I had the development responsibility for the V.32 product line modems.

So I was very familiar with all of this technology. I wrote about this in our book. So in the book there's a whole chapter dealing with trellis-coded modulation.

And I've taught many short courses dealing with coded -- trellis-coded modulation.

Q. Where did you teach those courses?

A. I taught various short courses -- I don't know if it's in my CV.

For the last, maybe 20 years, I've taught short courses all over the world. Typically industrial short courses. I started, let's say --

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I did the first one in Israel. I taught at UCLA. I taught in a company, CEI, in Europe.

And my first five, six years was all about signal processing. There's a whole section on trellis coding.

Q. Are these short courses listed in your CV?

A. Probably not. Because they are -- they are consulting. So I just -- just as I don't list in there expert witness consulting. I've done a lot of that.

I think I've taught now -- because I just taught one -- more than 50 short courses. And the earlier ones were predominantly on signal processing.

I was writing a book. I taught a course at Princeton University which is listed here. Yeah, adjunct professor, E 526 dealt with trellis coding.

When I was at -- visiting professor at Columbia I taught two communication theory courses and I covered trellis coding in those courses.

Q. I also see from your CV that you have 47 issued patents, and six of those -- six of the --

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six patent applications that are pending.

How many of those address trellis coding modulation?

A. There's certainly one that deals with combining trellis coding and decision feedback equalization. That's the only one I can recall now.

Q. Which patent is that? Can you recall the number?

A. No, I cannot.

Q. Did that particular patent encompass a novel means of performing trellis-coded modulation?

A. I assume so, otherwise it wouldn't have been issued.

Q. You mentioned it's a combination of trellis-coded modulation and an equalizer.

A. Yes.

Q. Is the trellis-coded modulation that is used in that patent the type that's known in the prior art?

A. Like many of these systems, you build building blocks together and together.

You know, the patent was issued.

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There were some novel interplay between the decision feedback equalizer and the trellis-coded system.

Q. Do any of these technical papers or patents address Viterbi decoding?

A. Well, the patent deals with Viterbi decoding. There's no paper that explicitly deals with Viterbi decoding.

Let me just...

(The witness reviews document.)

A. There's one, I may have left a paper out. It dealt with application of Viterbi decoding to fiber optics systems. And it was in the Bell System technical journal. I may have left it out of my CV inadvertently. I'm looking to see if it's included. I forgot about it.

Oh, there it is. Reference 76. Deals with -- reference 76, paper 76, "Optimum Direct Detection of Digital Fiber Optic Communication Systems." It deals with applying Viterbi algorithm to fiber optic communication system.

Q. Okay. And that Viterbi algorithm is used to decode what type of code?

A. It's -- the Viterbi algorithm is a

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generic technique that does some form of deconvolution. This was to deal with a polarization dispersion in a fiber optic system. We're dealing with channel impairments.

Q. So, is it fair to say that you made no significant contributions to trellis-encoded modulation?

MR. TROPP: Objection.

A. Absolutely not. I brought it to practice. I was responsible for commercializing the first system that used trellis coding.

Q. So you were involved in commercializing the system?

A. Design of the system.

Q. As well as the design of the system?

A. Yeah.

You know, a lot of guidance to Lee-Fang Wei's nonlinear trellis-encoded became part of V.32, came about because I was doing my job, and I asked him a question. I said, Ungerboek has got this code. And in order to make a promotional system we need to have a rotational at variance.

So that's what managers do. You don't want to compete with your people. Nick Viterbi is

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a very bright guy. I hired him. I recognized the opportunity. I considered that a great contribution. It was so recognized in the company by people that observed me.

Lee-Fang Wei came up with the rotationally invariant trellis code.

So I strongly dispute your characterization.

Since 1979 I have been a manager and then an executive, and one of the things you learn is you don't compete with your people. You ask the right questions. Otherwise, you piss people off.

(Continued on following page to include jurat.)

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MR. KOLMYKOV: Fair enough. This is the end of the deposition, and I thank you for your time.

THE WITNESS: Sure, thank you.

THE VIDEO OPERATOR: The time is 5:39 p.m., June 23, 2008. This is completes the deposition of Richard Gitlin.

(Time noted: 5:39 p.m.)

____
RICHARD D. GITLIN

Subscribed and sworn to before me this _____ day of _________, 2008.

____

CERTIFICATE

STATE OF NEW YORK)
: ss.
COUNTY OF NEW YORK)

I, AMY KLEIN, a Shorthand Reporter and Notary Public within and for the State of New York, do hereby certify:

That RICHARD D. GITLIN, the witness whose deposition is hereinbefore set forth, was duly sworn by me and that such deposition is a true record of the testimony given by the witness.

I further certify that I am not related to any of the parties to this action by blood or marriage, and that I am in no way interested in the outcome of this matter.

IN WITNESS WHEREOF, I have hereunto set my hand this_24th day of _June _, 2008.

____
AMY KLEIN

------------------ I N D E X ------------------

------------------ EXHIBITS ------------------

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